1983

Strategy for improving the efficiency of duff moisture content and duff structure estimates

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A STRATEGY FOR IMPROVING THE EFFICIENCY OF DUFF MOISTURE CONTENT AND DUFF STRUCTURE ESTIMATES

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B.A. Biology, Colgate University, 1977

Presented in partial fulfillment of the requirements
for the degree of

Master of Science in Forestry

University of Montana

1983

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8-1-83

Date

Hillhouse, Margaret I., M.S. 1983 Forestry

A Strategy for improving the efficiency of duff moisture content and duff structure estimates. (59 pages)

Director: Donald F. Potts DFP

The purpose of this study was to 1) provide a sampling strategy that produces an efficient estimate of duff moisture and 2) to determine the seasonal and spatial variability in duff moisture content and duff structure. A systematic sampling grid was established on five sites representing two habitat series on the Lolo National Forest. Samples collected over a full drying season provided statistics to calculate the sample size required to obtain an estimate, at an allowable error of 20% and 95% confidence. Stratification by three moisture regimes was achieved by exploring the spatial distribution over the season. A significant reduction in sample size was achieved through stratification while retaining the desired precision of the estimates at the same confidence level. With practice by fuels managers, this technique should decrease time and costs of sampling.

Acknowledgements

Encouragement and support for this project came from many directions. Without the help of friends, roommates and family - setting out plots, sampling and computer analyses, the project would still be unfinished.

I offer special thanks to my brothers Ken and Matt who toiled for long hours of dusty sampling for little reward, to Bob Loveless for his assistance establishing several of the plots and many long hours on the computer, to Dr. Hans Zuuring for his advice and help with the statistical analyses, and to Dr. Don Potts who has tolerated me and my diversions for three years. Kevin Ryan also deserves special thanks for his professional advice.

This project was funded by the USDA Forest Service under Cooperative agreement INT-80-107-CA.

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CHAPTER I

INTRODUCTION

Prescribed fire is a preferred method for site preparation on many sites in the intermountain west, particularily on steep slopes. Regeneration of commercially important conifers such as *Larix occidentalis* (western larch) and *Pseudotsuga menziesii* (Douglas-fir) is enhanced on sites with mineral soil exposure and duff reduction as prepared by fire (Schmidt et al. 1976). Furthermore, prescribed fire can be cost effective (Baumgartner 1982).

The vegetation of the intermountain region has been strongly affected by fire (Davis, Clayton and Fischer 1980). Natural fire occurence and severity is determined by meteorolgic events and fuel conditions. Slope, aspect, and elevation, by controlling energy receipt, moisture regimes and decomposition rates, influence fire severity and duff and litter accumulation. With timber harvest in old growth stands at higher elevations or in areas unaffected by the devastating fires of 1910, duff reduction has become a major objective of site preparation. When prescribed fire is properly conducted, it can achieve silvicultural objectives as well as simulate the natural fire cycle.

Van Wagner (1972), Norum (1975, 1977), Shearer (1975), Artley et al. (1978), and Sandberg (1980) have shown a strong relationship between duff reduction and duff moisture content (Figure 1). Duff moisture, the amount and size of fuels, slope, aspect and cover type, and meteorologic events are integral components of fire behavior predictions and models (Rothermal 1972; Albini 1975; Sandberg 1980). Sandberg's model was unsatisfactory on the sites that Little et al. (1982) studied within the Willamette National Forest in Oregon. Fire danger rating systems (Deeming et al 1977; Van Wagner 1974) also include these components but the National Fire Danger Rating System (NFDRS) was designed primarily for roundwood moistures rather than duff moisture contents.

Brown (1974) provided a standard method for measuring fuel inventories and Norum (1977) described techniques for moisture content appraisal. Duff moisture and duff depth, however, have extremely variable distributions, leading to erroneous estimates for prescribed burning unless a large sample size is used. Duff sampling is tedious and time consuming, thus improving the sampling efficiency and providing a dependable estimate or description of the variability is of great interest to fire managers. High elevation, north slopes, because of lingering snowpacks and less direct radiation than south slopes, have short drying seasons and thus perhaps epitomize problem areas for duff reduction by prescribed fire.

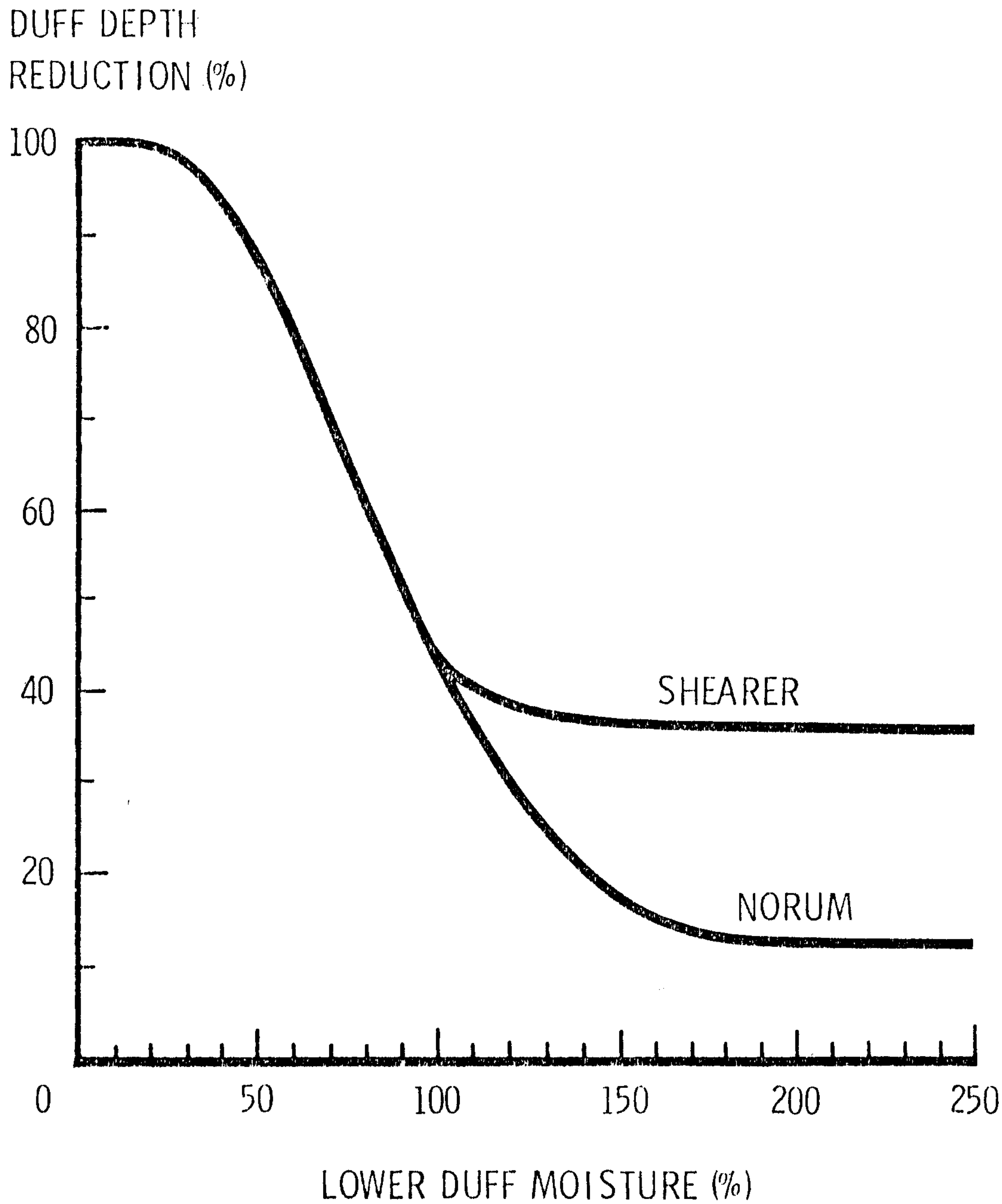


Figure 1. Percent duff depth reduction as predicted from lower duff moisture content from broadcast burning of slash and non-slash in the Douglas-fir/western larch type.

CHAPTER II

STUDY DESIGN

The purpose of this study was to describe the variability in duff moisture content and duff structure and to devise a sampling scheme which can identify homogeneous subgroups and thus reduce variation. The specific research objectives were to:

1. determine sample size and sampling procedure necessary to efficiently estimate duff moisture content;

2. determine the seasonal and spatial variation in duff moisture content and duff structure by systematic sampling under two cover types;

3. verify the predictability of measured moisture contents on the chosen sites from the duff moisture components of the Canadian Fire Weather Index (FWI) and National Fire Danger Rating System (NFDRS) models.

The management objective for this study was to provide a technique for obtaining a reliable estimate of an area's duff moisture for prescribed fire planning.

The *Abies lasiocarpa* (ABLA) cover type, typified by *Abies lasiocarpa*/*Menziesia ferruginea* (ABLA/MEFE) habitat type (Pfister et al. 1977) and characteristic of high elevation north slopes, was the focus for exploring within site and between site variations with respect to duff moisture content and duff structure. The widespread *Psuedotsuga menziesii* (PSME) cover type, specifically the *Psuedotsuga menziesii*/*Physocarpus malvaceus* (PSME/PHMA) habitat type representing drier sites at lower elevations, was selected to provide a between type comparison.

SITE DESCRIPTIONS

The study sites were located in Missoula County, Montana within the Lolo National Forest (Figure 2). The Lee Creek study site (lat. 46 40′ N., long. 114 33′ W.) had an ABLA cover type before harvest using the seedtree method in 1977. Residual stems were western larch and Douglas-fir. The Granite Ridge study site (lat. 46 41′ N., long. 114 34′ W.) supported an old growth ABLA stand before clearcutting in 1980. With precipitation less than the 64 cm (25 in.) annual average, high elevation, north slopes as selected for this study, became prime targets for prescribed burning, thus the study was limited to these two ABLA sites. The site descriptions, along with those for the PSME sites, are given in Table 1.

The three PSME sites support timber resulting from the 1910 fires but also show signs of harvest. The Wagon Mountain Road study site (lat. 46 49′ N., long. 114 28′ W.) is an open, almost parklike stand, where annual precipitation averages about 60 cm (23 in.). The Cowboy Gulch study site (lat. 46 54′ N., long. 113 55′ W.) is across the Clark Fork River valley from the Deer Creek site (lat. 46 51′ N., long. 113 55′ W.). Both sites receive an average of 38 cm (15 in.)

precipitation annually. Deer Creek was harvested in the summer of 1982 after the study was completed. Sites selection criteria was to minimize the between site variation within each cover type.

Table 1 - Site Descriptions

	Elevation (meters)	Aspect	Slope (%)	Soil series	type
ABLA sites					
Lee Creek	1830	N 10 W	55	Petty and Holloway	loamy-skeletal, mixed Andic Cryochrepts
Granite	1770	N 10 E	17	Petty	same
PSME sites					
Cowboy Gulch	1680	S 10 W	44		
Deer Creek	1280	N 46 E	48	Winkler	loamy-skeletal, mixed frigid Udic Ustochrepts
Wagon Mtn.	1650	S 5 W	26	Mitten	loamy-skeletal, mixed frigid, Andic Dystric Eutrochrepts

SAMPLING PROCEDURE

The sampling was at two to four week intervals through the summer of 1981 and early summer of 1982 in order to obtain a drying curve representing an entire burning season. Cowboy Gulch was sampled four times in 1981. Deer Creek, Wagon Mountain Road and Lee Creek were each sampled 5 times and Granite Ridge, because of the late plot

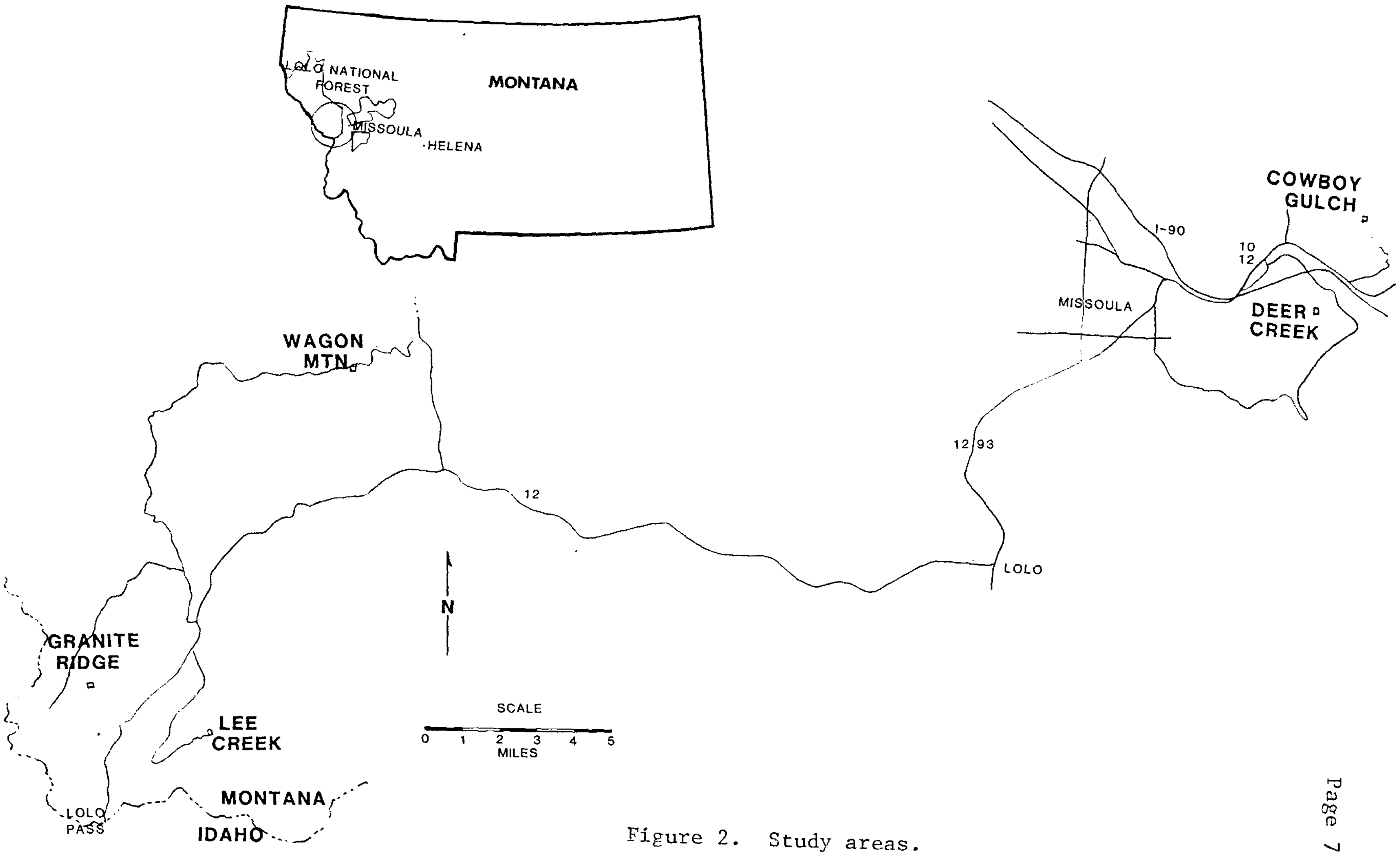


Figure 2. Study areas.

establishment, was sampled only three times. All sites were sampled twice in 1982. A systematic sampling scheme was used as it would eliminate a bias otherwise introduced for sampling convenience.

A grid of 28 permanently staked points was randomly located at each site and oriented across the slope. Sample points were spaced 10 meters apart and a one meter square plot was established at each point. Duff samples were placed in 7.6 cm. diameter soil tins sealed on site and weighed immediately upon return to Missoula. The preservation of vertical integrity was not required for the analyses. Moisture content was gravimetrically determined after drying in a standard drying oven at 80 C.

$$\% \text{ moisture content} = \frac{\text{wet weight-dry weight}}{\text{dry weight}} \times 100 \qquad \text{Equation 1}$$

The duff was allowed to dry until the weight stabilized. Twenty-four hours was generally sufficient, with very moist duff requiring 2 to 3 days.

After the first two sampling dates at Lee Creek, the duff from the ABLA sites, thicker than PSME duff and with a distinct layering, was separated into upper and lower samples for individual analyses as in other studies (Artley et al. 1978; Sandberg 1980). The layers were distinguished by degree of decomposition, approximating the fermentation and humification layers (F and H). Because the duff on the PSME sites was thin (overall mean = 2.5 cm.), two replicates were taken. On all sites, thickness of each layer or depth to mineral soil was also recorded when each sample was extracted. Thus the depth measurements do not represent a seasonal continuum from one set of points.

The sites were each instrumented with a hygrothermograph and a maximum-minimum thermometer, exposed 4 feet above ground in standard cotton-region type instrument shelters. Non-recording precipitation gauges were located within five meters of the shelters. Data were collected at weekly intervals. These data were used for input to the computerized versions of the Canadian Forest Fire Weather Index (Van Wagner and Pickett 1975) and the National Fire Danger Rating System *.

* DANRAT, unpublished fire danger rating program, North Central Forest Experiment Station, on file at the University of Montana School of Forestry.

CHAPTER III

ANALYSES

Assessing the variations in duff depth and duff moisture content were the objectives of this study. Duff depth was plotted over moisture content for each sample to clarify their relationship. Both mean depth and mean moisture content were plotted over time (Julian Calendar) to exhibit any seasonal trends, with samples from 1981 and 1982, years with dissimilar weather, considered as one season. Upper and lower mean duff moisture contents were separately analyzed on the ABLA sites.

Not anticipating any seasonal patterns, an Analysis of Variance (ANOVA) was performed on the duff depth data to test the equality of the mean depth measurements for each site and each ABLA layer.

$$Ho: \quad \mu_1 = \mu_2 = \ldots = \mu_m \qquad\qquad m = \text{samples per site}$$

Timelag is the equilibrium response of a substance to environmental change. Deeming et al. (1977) defined timelag as the time necessary for a fuel particle to lose $(1 - e^{-1})$ or about 63% of the difference between the initial moisture content and the equilibrium moisture content. An estimate of timelag can be calculated by assuming the exponential relationship of Fosberg (1977a) and Van Wagner (1979, 1982):

$$\frac{M - E}{Mo - E} = \frac{F}{Fo} = e^{-kt} \qquad\qquad \text{Equation 2}$$

where: Mo = initial moisture content,
M = current moisture content,
E = equilibrium moisture content,
Fo = potential moisture change,
F = actual moisture change,
k = log drying rate and reciprocal of timelag, and
t = elapsed time.

Measured moisture content data from each site were used to determine the time in days for the moisture content to drop to 37% of the peak value.

The weather data were used in the FWI model (Van Wagner and Pickett 1975) to calculate the Fine Fuel Moisture Codes (FFMC) and the Duff Moisture Codes (DMC) for the drying season at each site. The FWI model requires input of daily noon temperature, humidity, windspeed (especially for FFMC) and 24-hour precipitation totals. Windspeed, not measured, was given a low value (3 km/hr) under the assumption that in mountainous topography and under standing timber, windspeed is minimal. As non-recording precipitation gauges were used, the requirements for 24 hour totals were met by adjustments of weekly totals corresponding to the hygrothermograph records. The weather data were also used as input to DANRAT (see footnote on page 9). The duff codes and timelag fuel estimates generated from these models were compared to the measured data.

Statistical theory allows estimation of a sample size, n, based on the sample coefficient of variation ($s/\bar{x}$) given an allowable error, a, and a desired level of confidence. If the allowable error a, is defined by:

$$a = \frac{\bar{X} - \mu}{\bar{X}} \qquad \text{Equation 3}$$

then

$$n = \left(\frac{a^2}{t^2 CV^2} + \frac{1}{N}\right)^{-1} \qquad \text{Equation 4}$$

or

$$a^2 = t^2 CV^2 \ (1/n - 1/N) \qquad \text{Equation 5}$$

where: t = value from Student's t-distibution with 27 degrees of freedom at a specified confidence level,
CV = the coefficient of variation,
N = Population size,
n = Sample size.

By letting:

N = Population size = 1800 m (30 x 60m plots) and
n = Sample size = 28 m (28 points of one square meter),

the errors in moisture content estimation were calculated. Then, ignoring the finite population correction factor, Equation 4 was simplified to:

$$n = \frac{t^2 CV^2}{a^2}, \qquad \text{Equation 6}$$

which was used to calculate sample size for both depth and moisture content samples. Stauffer (1982) described this procedure and provided a table of sample sizes for a full range of CV's at selected allowable errors.

The systematic sample provided a framework to look at the areal distribution of moisture content. A mapping package on the University of Montana DEC-2060 computer (SYMAP) was used to generate maps of the relative moist, mesic, and dry areas for each sample. The range of values was equally split to define the moisture regimes. The regions were superimposed on the sampling grid with linear interpolation (Harvard Univ. 1975) providing intermediate values. By determining the areal contribution of each regime, a stratified sample n was calculated.

The population mean from a stratified sample is estimated as follows:

$$\bar{Y}_{st} = 1/N\ (N_1 y_1 + N_2 y_2 + N_3 y_3) \qquad \text{Equation 7}$$

where $N = N_1 + N_2 + N_3$

The weighted sample size can then be determined:

$$\Sigma\ n = t^2 \left(\sum_{i=1}^{3} W_i s_i^2 / \bar{Y}_{st}^2\right) /\ a^2 \qquad \text{Equation 8}$$

with t and a as defined above,

W_i = the proportional weighting factor as determined from the maps or $\dfrac{\text{area of i-th strata}}{\text{total area}}$

s_i^2 = the variance of strata i.

Several schemes for sample allocation exist for distributing samples among strata (Mendenhall et al. 1971). Proportional allocation was chosen over Neyman allocation, because the latter requires an estimate of sample variance which may not always be possible. The calculations for proportional allocation are also simpler.

CHAPTER IV

RESULTS AND DISCUSSION

Chrosciewicz (1978) found a positive relationship between duff moisture content and duff depth on most of his sites. Figure 3 is a composite of all the samples from Lee Creek and typifies the low correlation found on all sites. A strong correlation between duff depth and moisture content, which could greatly simplify sampling, was not observed probably for several reasons:

1. Overstory removal alters site exposure and can increase the extremes of environmental fluctuations. Shade and transpiration are affected.

2. Duff accumulation responds to hillslope processes and gravity. Litter is trapped uphill of stationary objects and will concentrate beneath the canopy.

3. Precipitation is redistributed by the forest canopy.

4. Duff has a timelag response to moisture inputs and losses.

DUFF STRUCTURE

Duff composition and structure are controlled by biotic factors and the microclimate of a stand. Variations reflect the type and frequency of disturbance. The spatial distribution of duff accumulation is a major sampling problem since fuel loadings as used in fire prescriptions

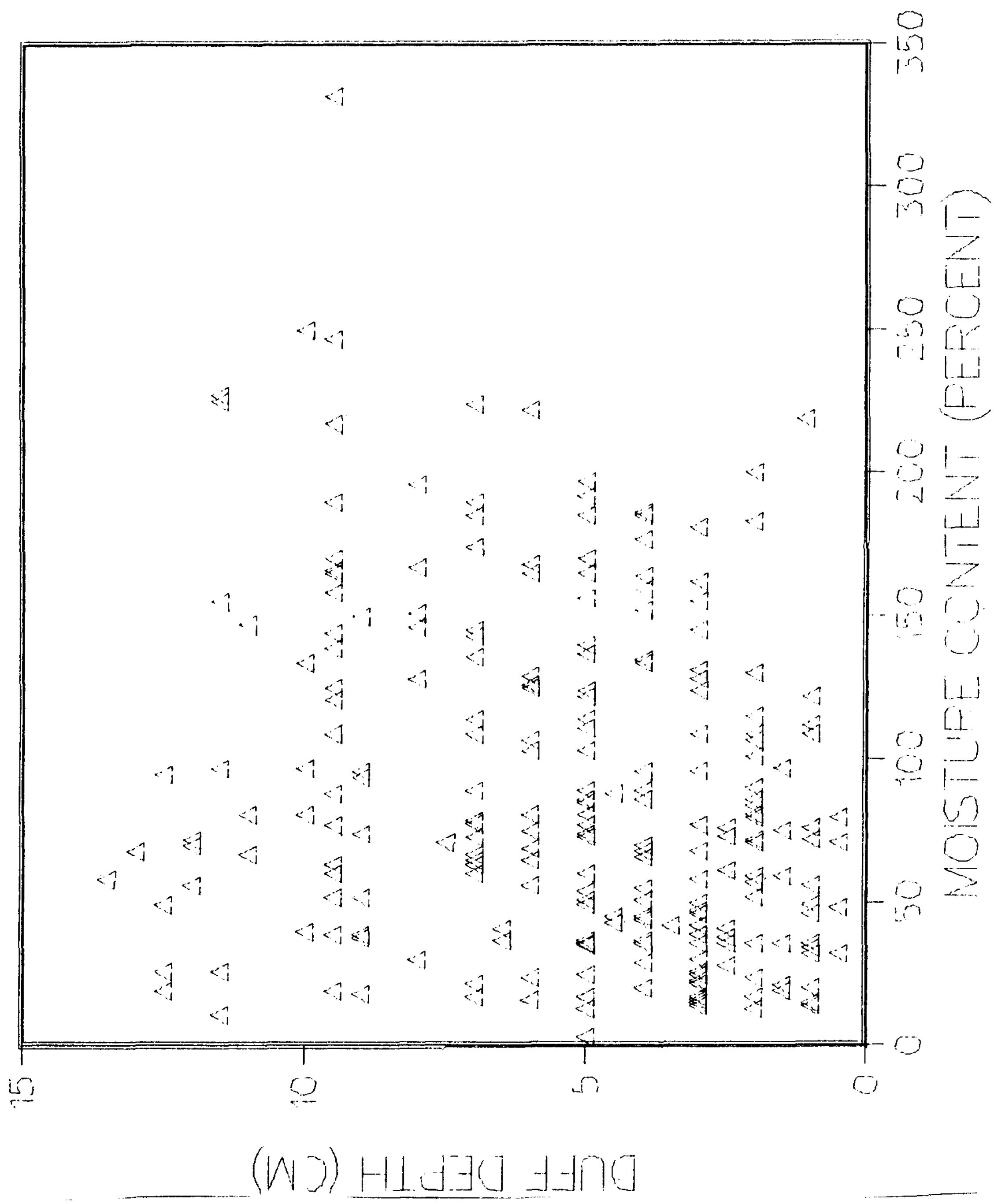
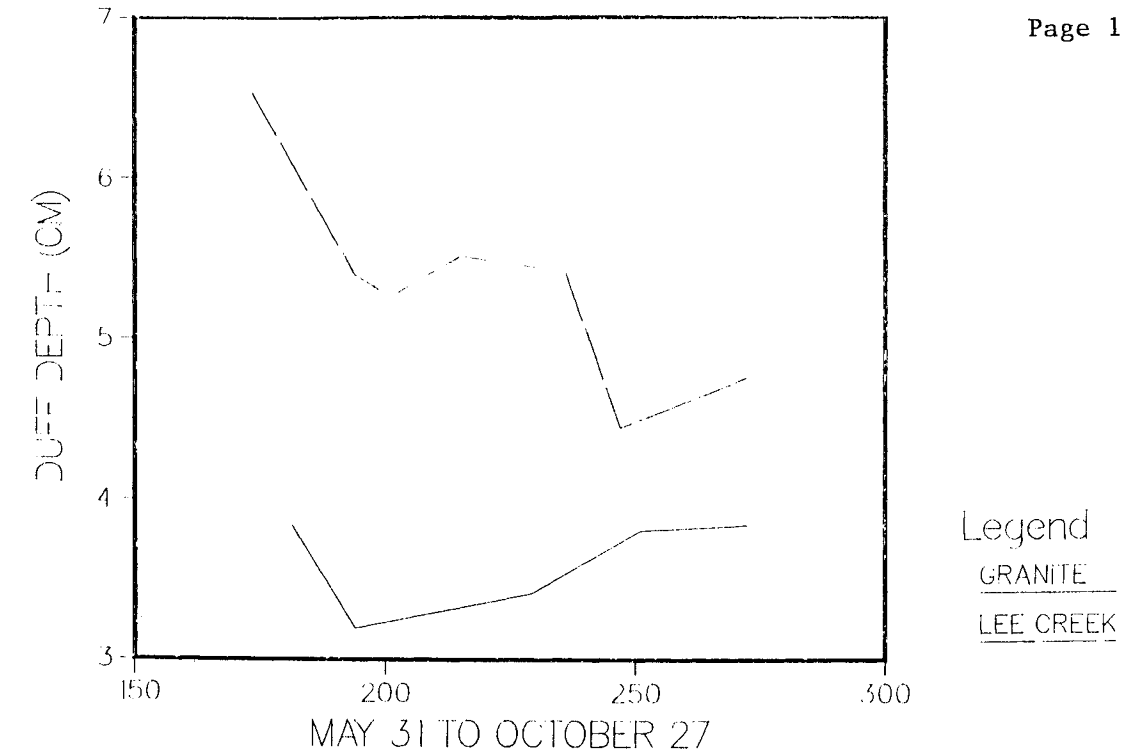
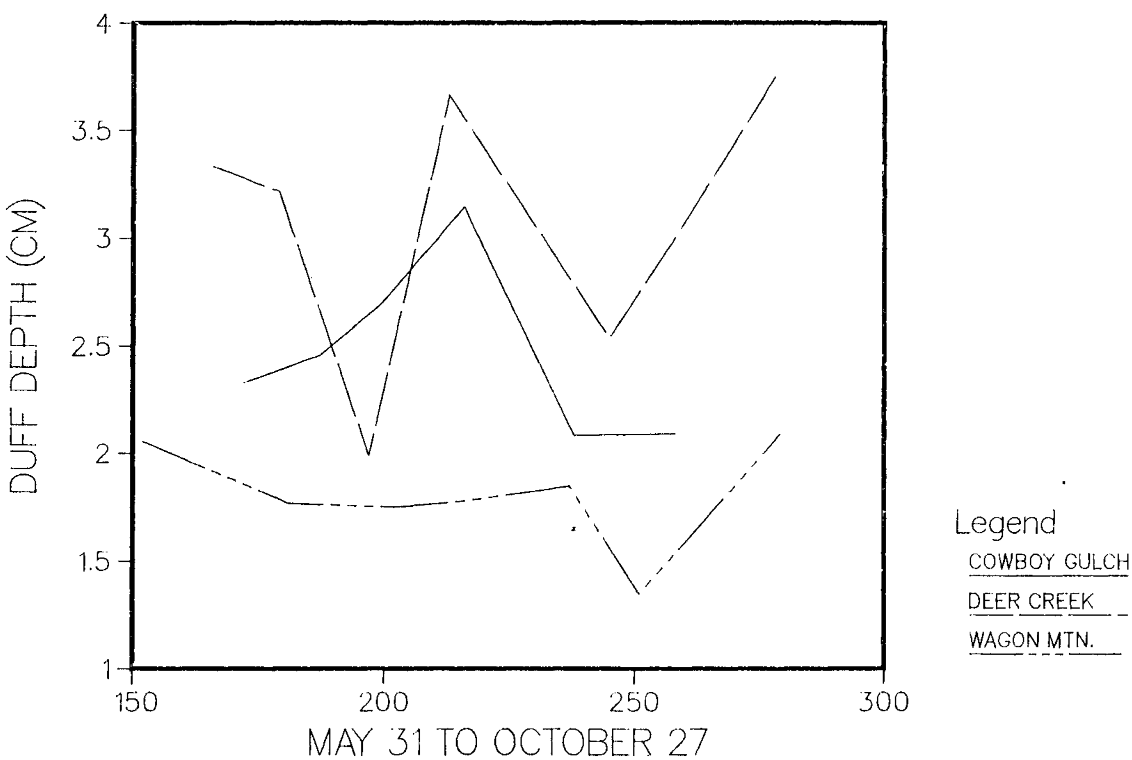


Figure 3. Scattergram of duff depth on moisture content for all samples at Lee Creek.

(Albini 1975) may be determined from depth measurements (Woodard and Martin 1980). On any of the study sites, depth measurements within a square meter, point replicates or from sample to sample, can vary by several centimeters. The overall depth ranges were 0.5 - 9.5 cm. on the PSME sites, and 0.5 - 6 and 0 - 9.5 cm. for the upper and lower duff layers, respectively, on the ABLA sites. However, over a season, the mean depth on a site should not vary significantly. In the intermountain region, potentially high decomposition rates stimulated by warm summer temperatures are balanced by limited moisture and litterfall during the growing season. Figure 4 shows the variation in mean duff depths on each site over time. As the depth data were collected by destructive sampling, these mean values do not represent a permanent sampling network. The fluctuations are due to sampling variations. The vertical line separates the two years.

The statistics and results of the one-way Analysis of Variance (ANOVA) for sample to sample mean depths on all sites are given in Table 2. The differences in the degrees of freedom (d.f.) reflect the sample frequency and procedure on each site. The ANOVA's for the three PSME sites and the ABLA upper duff sites were all significant at the 95% confidence level, suggesting that means differ during the season, although no pattern is implied. The ANOVA results for the lower and total duff samples from the ABLA sites are not significant at 95%, although Lee Creek lower duff is significant at 90%.





b)

Figure 4. Seasonal changes in duff depth: a) ABLA/MEFE sites; b) PSME/PHMA sites.

Under both cover types, large accumulations of duff and litter are often associated with large trees and buried rotting logs. When timber is removed, the duff is exposed to more radiation, accelerating

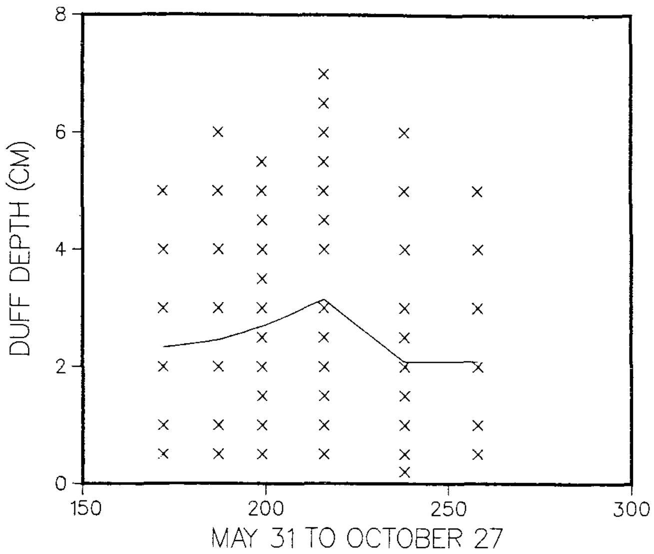
Table 2. One way ANOVA and associated statistics by site

Source	d.f.	Sum of Sq.	Mean Sum	F	Sig.
PSME sites					
Cowboy Gulch					
Sampling date	5	45.56	9.112	4.788	.0003
Error	330	628.064	1.903		
Deer Creek					
Sampling date	6	132.182	22.030	4.955	.0001
Error	385	1711.723	4.446		
Wagon Mountain					
Sampling date	6	20.006	3.344	2.231	.0396
Error	385	577.254	1.499		
ABLA sites					
Granite Ridge (upper)					
Sampling date	4	3.582	.890	2.620	.0377
Error	135	45.875	.340		
Granite Ridge (lower)					
Sampling date	4	6.511	1.628	0.654	.6254
Error	135	336.232	2.491		
Granite Ridge (total)					
Sampling date	4	10.114	2.529	0.734	.5706
Error	135	465.321	3.447		
Lee Creek (upper)					
Sampling date	6	490.634	81.772	17.124	.0000
Error	241	1150.841	4.775		
Lee Creek (lower)					
Sampling date	6	79.476	13.246	2.085	.0584
Error	145	921.259	6.354		
Lee Creek (total)					
Sampling date	6	75.440	12.573	1.260	.2765
Error	241	2404.568	9.977		

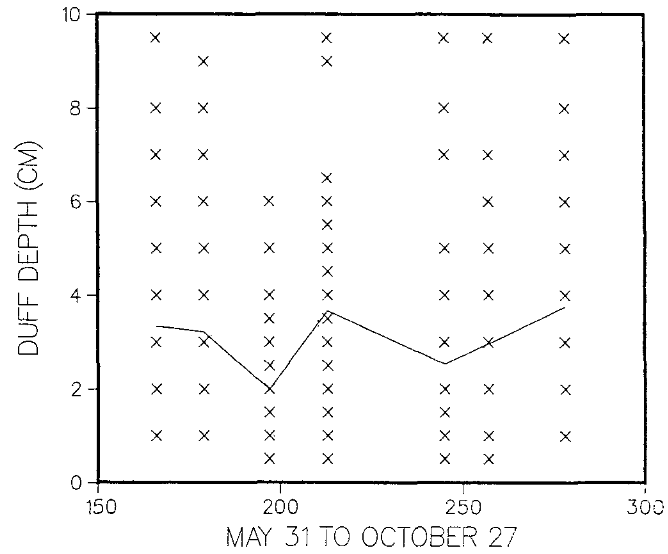
decomposition. Timber removal reduces litterfall onto the surface as well. A systematic sample may place sampling points within areas of accumulation, on rotting logs, or as likely in areas of little duff. Duff in open areas would tend to have greater temperature and moisture fluctuations than duff in shaded areas, affecting drying and decomposition rates. Therefore, while the overall duff layer may be consistently deep, the individual layers can be variable in response to heat and moisture fluxes through material of inconstant properties (Fosberg 1977b).

The significant F-tests are due to the high within site variation (Fig. 5) and may also be partially explained by the thin duff on the PSME sites and thin upper duff of the ABLA sites (see Table 3). A centimeter of difference around a low mean shows proportionally greater deviation from the mean than from a high mean value. The absence of significance between the other samples is expected as the deeper duff masks small deviations from the mean.

For the first two sample dates at Lee Creek (7-20-81 and 8-03-81) layers were not separated. These depth measurements were included in the layer analyses. Separation of upper and lower duff may also be highly subjective and up until the last sampling periods, the consistency of separation may be challenged. Moisture distribution and the associated cohesiveness of the organic material also influences the layer identification.



a)



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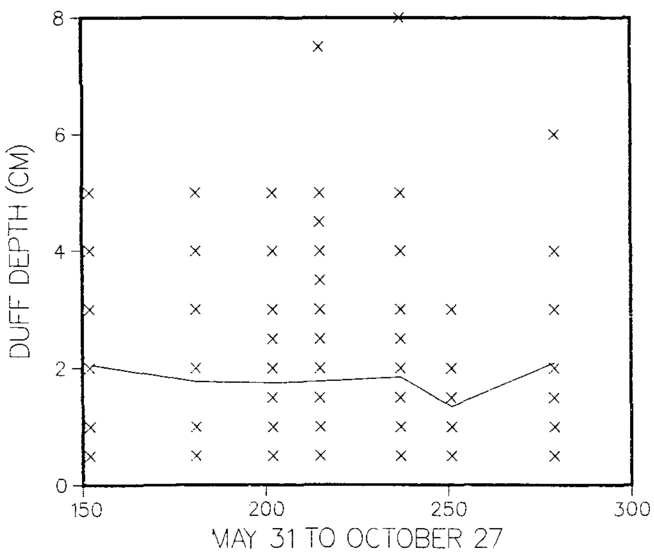


Figure 5. Mean duff depth (-----) and ranges (X X) from PSME sites: a) Cowboy Gulch; b) Deer Creek; c) Wagon Mountain.

Table 3 gives the sample sizes required for an estimate of duff depth on selected sites. For all sites, the coefficients of variation were consistently over 30% and as high as 87%. At an allowable error of 20%, and with 95% confidence, sample size can range from 12 to 76 samples (Stauffer 1982). The sample size of 28 used in this study was adequate to obtain an accurate estimate of mean depth for only 21 percent of the samples.

Table 3. Duff depth sampling statistics and estimated sample size based on Equation 7 and a = .20 with 95% confidence. The sites are identified by location (ie. C is Cowboy Gulch) and date of sampling. SD = Standard deviation, CV = coefficient of variation, n = sample size, U = upper duff, L = lower duff.

Site	Mean	SD	CV	n	Site	Mean	SD	CV	n
PSME sites					ABLA sites				
C621	2.33	1.16	.50	27	G630(U)	1.68	0.61	.36	15
C706	2.45	1.30	.53	30	G713(U)	1.23	0.57	.46	23
C718	2.69	1.39	.52	29	G908(U)	1.27	0.58	.46	23
					G630(L)	2.18	1.28	.59	36
D801	3.66	2.60	.71	51	G713(L)	1.96	1.46	.75	57
D902	2.54	1.82	.72	53	G908(L)	2.54	2.19	.87	76
D914	2.96	2.17	.73	54					
D005	3.75	2.35	.62	40	L622(U)	2.39	1.03	.43	21
					L713(U)	2.04	0.87	.43	21
W630	1.77	1.21	.68	47	L824(U)	1.80	0.89	.50	27
W803	1.77	1.42	.80	64	L622(L)	4.16	2.80	.67	46
W908	1.35	0.85	.63	41	L713(L)	3.35	2.50	.75	57
W006	2.09	1.14	.55	31	L824(L)	3.60	3.04	.84	71

In summary, duff structure is highly variable on a site, between sites of a cover type and between cover types. Brown and See (1981) were unable to find a reliable estimator of duff depth and downed fuel from stand age, aspect, slope and elevation. In a nonhomogeneous region, duff depth estimates must be made on a site by site basis as the stand history and stand parameters will be the controlling variables. Only broad generalizations on the relative depths may be made; in this study duff was thicker on ABLA sites with less available energy and longer fire-free intervals, than duff on PSME sites with higher available energy and more frequent fires. Seasonal trends do not conclusively exist. A sample size greater than when determined by equation 7 will reduce the error term, a, or increase the confidence of the estimate.

DUFF MOISTURE

Duff moisture content, unlike duff depth, exhibits both spatial and seasonal variation. The spatial variation is determined by biotic and physical site factors. The seasonal variability is characterized by a drying trend over the summer, responding to increased energy inputs and lack of summer precipitation (Figure 6). Both the NFDRS (Deeming et al. 1977) and the Canadian Fire Weather Index (FWI) (Van Wagner 1974) recognize this pattern and utilize it in the respective models.

Seasonal Variation

Figure 6 illustrates mean moisture content for each site plotted over time; again the vertical line separates the two years of data. The moisture data for all sites approximate an exponential decay model until rewetting commences in mid to late September (Julian day 258 =

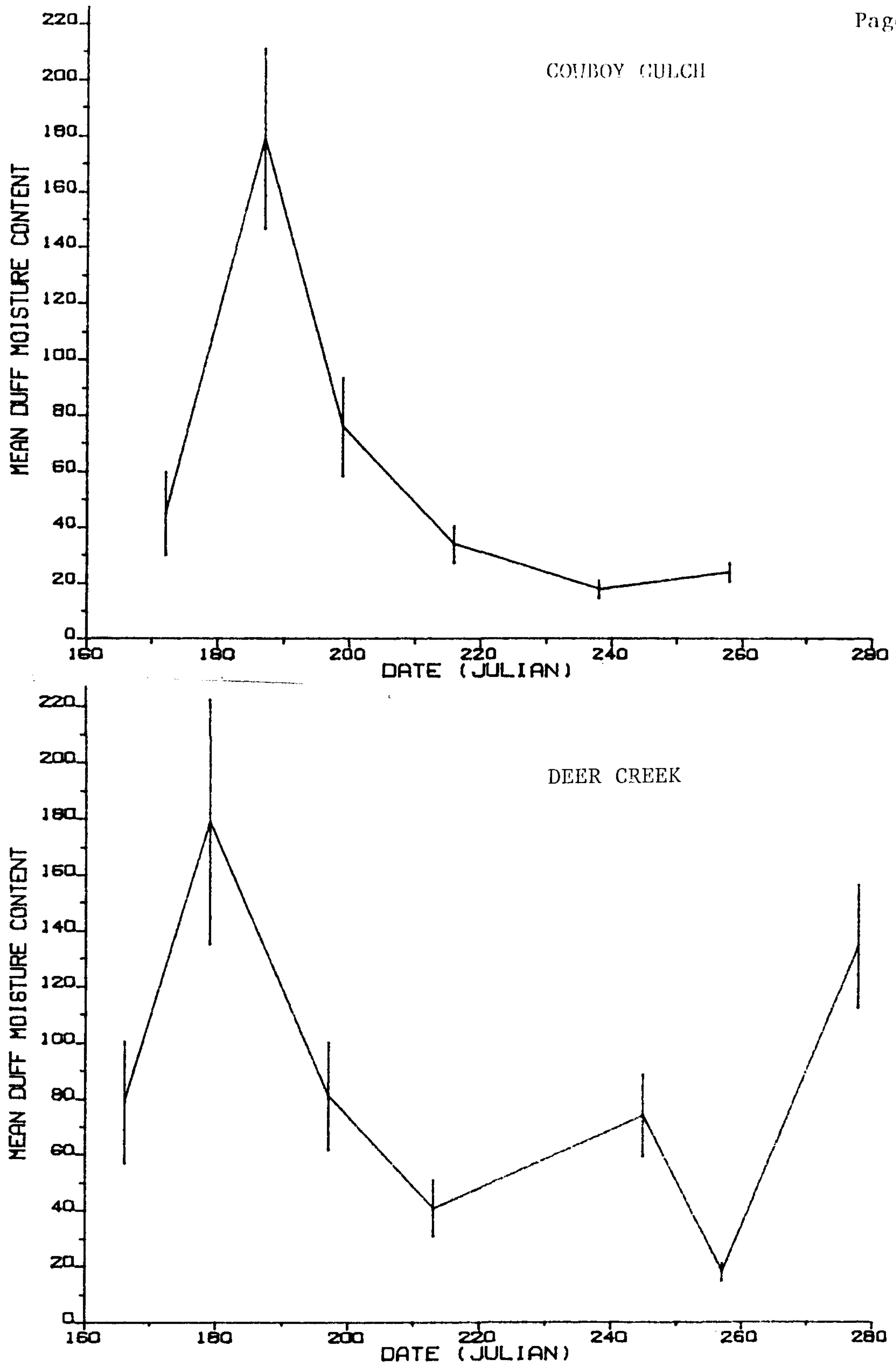


Figure 6. Seasonal changes in duff moisture content. The vertical bar indicates $\pm$ one standard deviation.

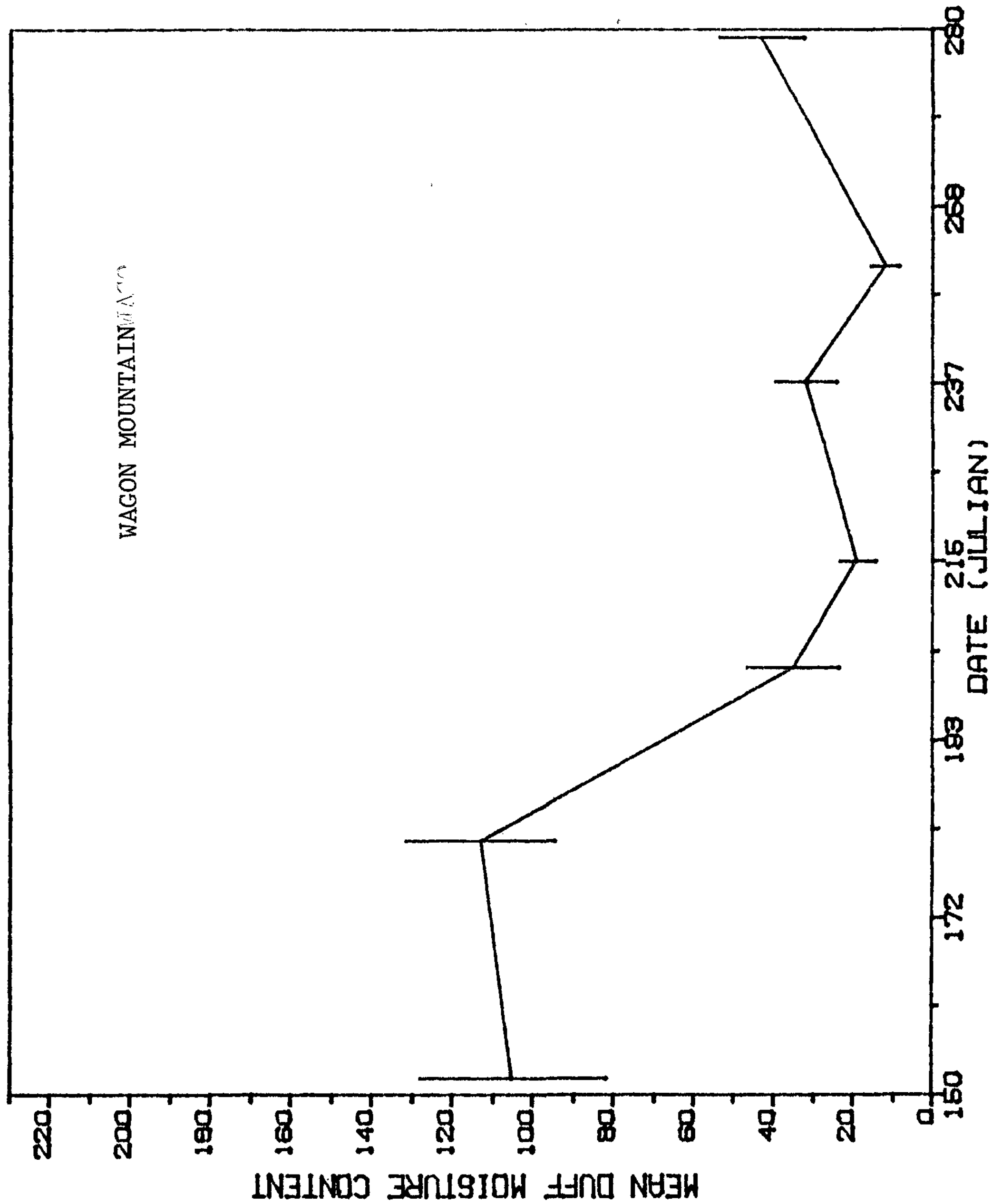


Figure 6. Seasonal changes in duff moisture content (cont'd).

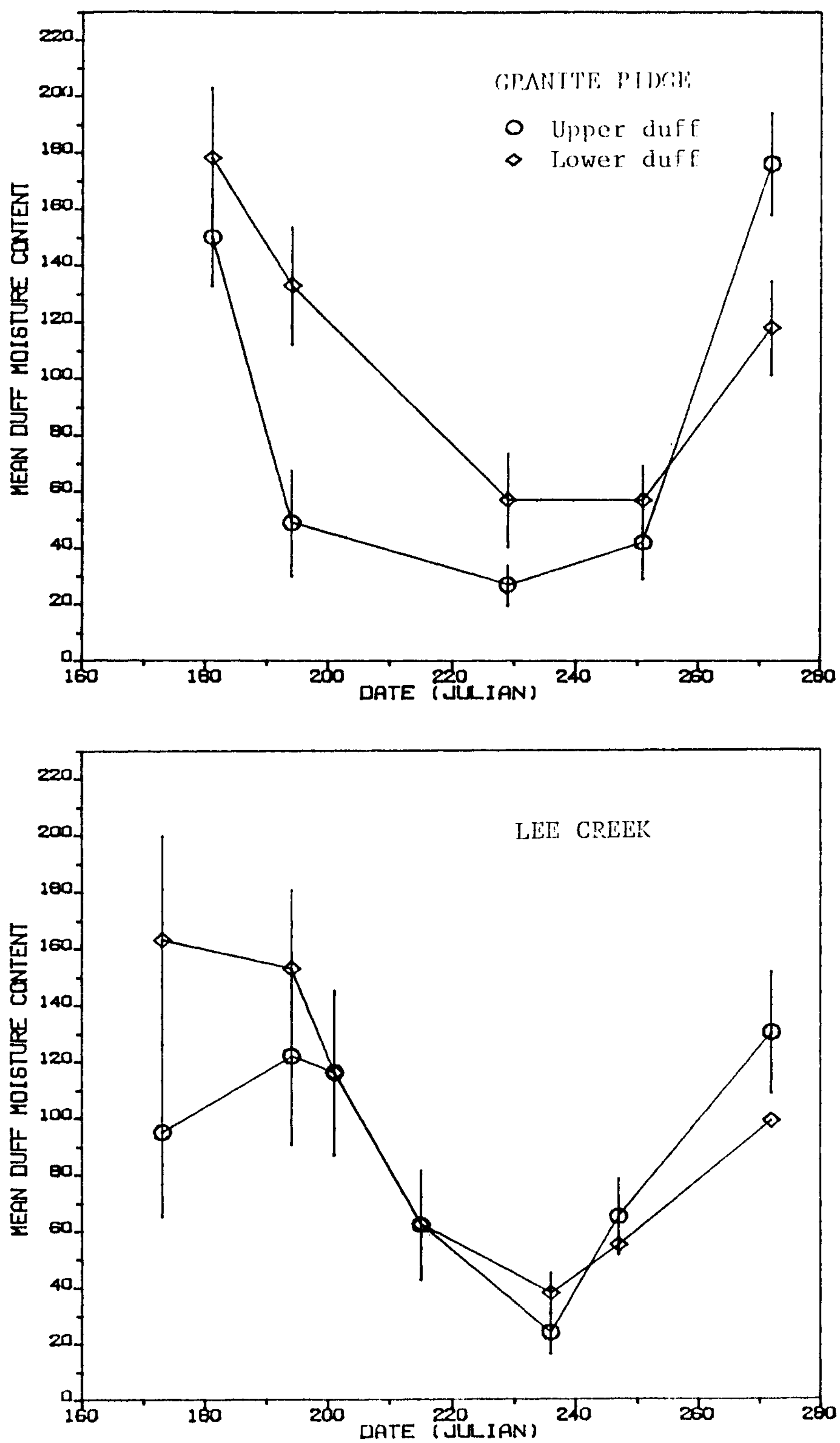


Figure 6. Seasonal changes in duff moisture content (cont'd).

Sept. 15). When the season of moisture recharge begins, the curves for the upper and lower duff layers show dissimilar timelags. Lower duff, more consolidated, has a slower response to environmental changes (Fosberg 1977b) and may thus remain on a drying phase as the upper duff begins rewetting. Henderson and Muraru (1968) attributed severe British Columbian fires of 1967 to this situation.

Comparing the two cover types, an earlier minimum moisture content is achieved on the PSME sites, reflecting the differences in energy loading. An estimate of timelag, the time for the duff to lose approximately 2/3 of the initial moisture content also supports this observation. The timelag was estimated at 19 days for the PSME sites and 27 days for the two ABLA site, if the layers are averaged.

PSME sites

Cowboy	Deer Creek	Wagon
17 days	22 days	19 days

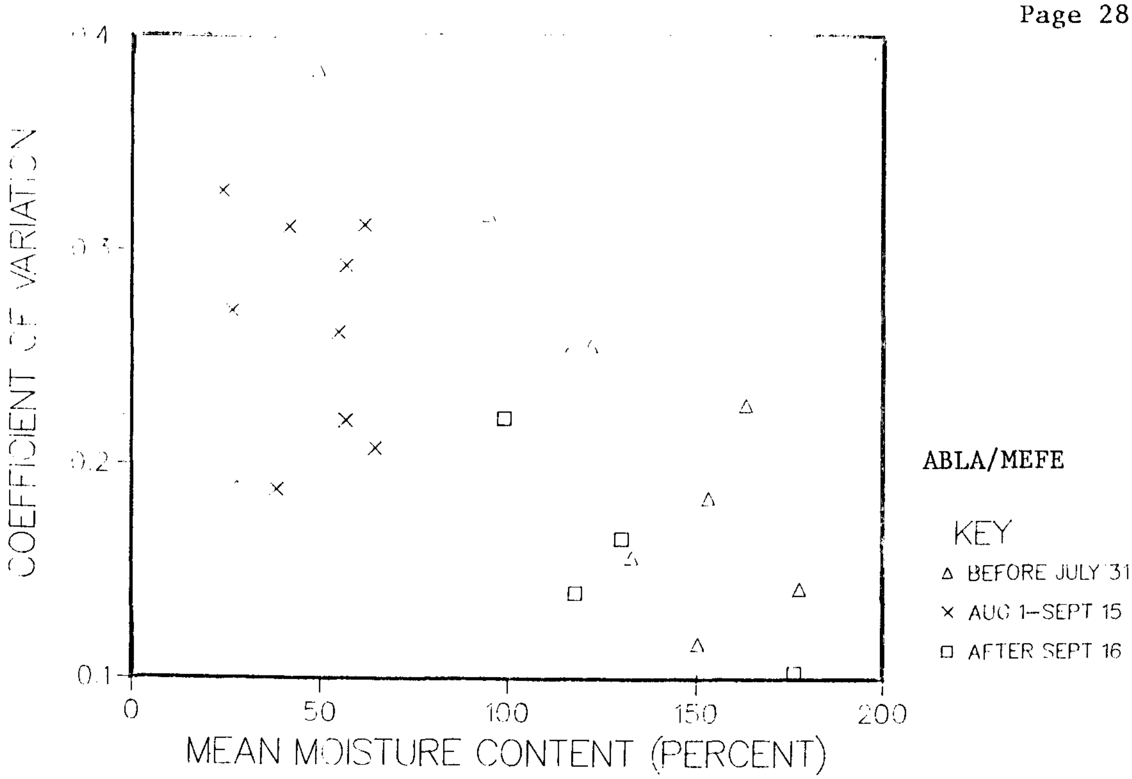
ABLA sites

Granite		Lee Creek
12 days	upper	28 days
44 days	lower	26 days

The PSME sites, on which the duff layers were of similar thicknesses and composition, show a greater consistency in estimation than the ABLA sites. Upper duff at Granite Ridge responded rapidly but the lower duff had a slow response. Unexpectedly, Lee Creek had similar timelags for the two layers, but this situation may have partially resulted from the non-separated layers for the July 20 and August 3 (L720 and L803) samples.

Errors may have arisen from three other sources. Sampling with greater intensity would increase the probability of measuring the extremes. The minimum and maximum moisture contents for any of the sites may have occured in the two to three weeks between samples. The other source of error is the interrupted season. Van Wagner (1982) showed than the initial moisture content should not affect the timelag calculations, but he did not investigate the effects of combining two years of data. Although the response of the material to drying should be consistent, the regional weather patterns of the two years were dissimilar. The high precipitation in the winter of 1981-1982 may have delayed the start of the drying season for 1982 by a week or more. Lastly, the transpiration of understory vegetation, whose roots can occupy the duff, is not included in the timelag calculations. The five sites differed in amounts of vegetation, thus this could be another error source.

Where the mean and variance change together, as occurs for these data, the coefficient of variation (CV) is a useful measure. Plots of the CV versus the mean for the two cover types are shown in Figure 7. For the PSME sites (Fig. 7b) two groupings seem possible. The early season and very late season samples approximate an inverse relationship with higher moisture contents showing lower coefficients of variation. The late season, driest samples (MC $\leq$ 75%), are clustered around 28 to 48% variation.



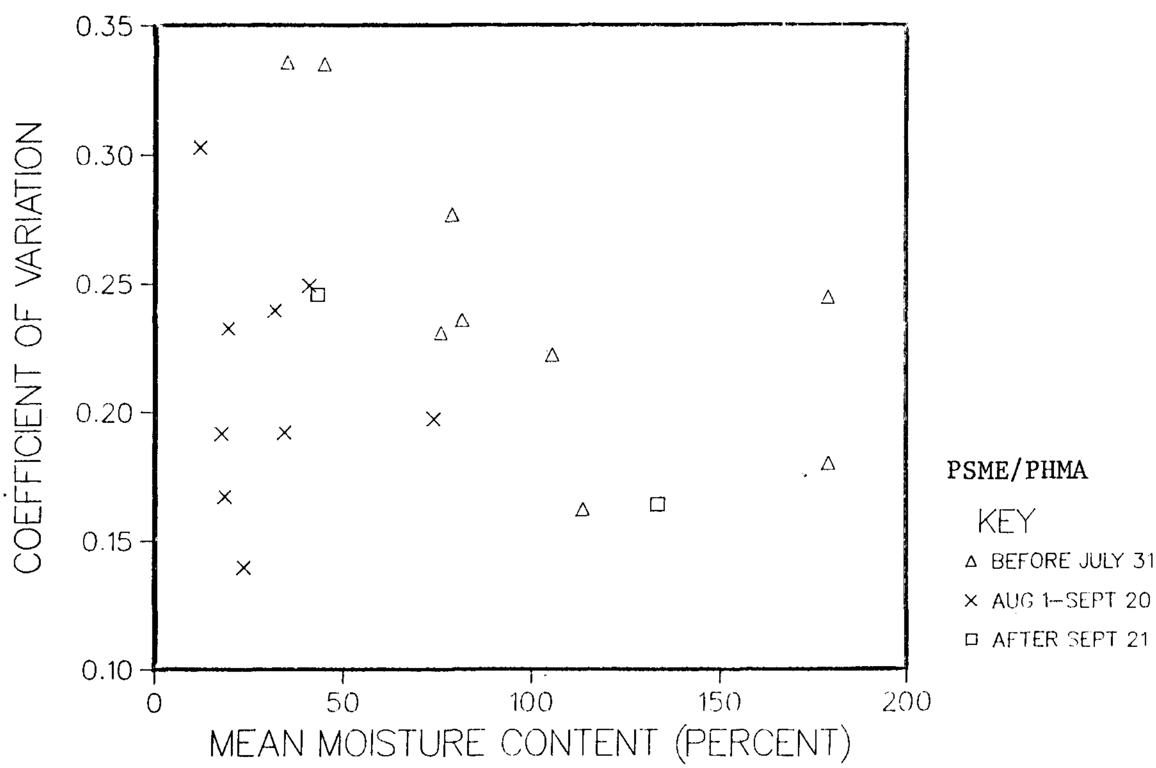


Figure 7. Coefficient of variation versus mean moisture content as distributed by season.

The ABLA sites are not so easily grouped but the entire range suggests an inverse relationship, where low moisture contents have high variability on a site (Figure 7a). Chrosciewicz (1978) noted that the variability in moisture content in the spring on Jack pine (Pinus banksiana) did not fit the pattern described by later dates, although neither variation was described.

Owe et al (1982) found the CV to be inversely related to soil moisture content with less variation at greater horizon thicknesses. As the regression points fell anywhere below the curve defined by CV = $\exp(-5.85X)$, accurate estimates of variation cannot be assumed by this procedure, however, the curve provides an estimate of the maximum variation expected. A maximum required sample size at any moisture content could be determined by such a relationship.

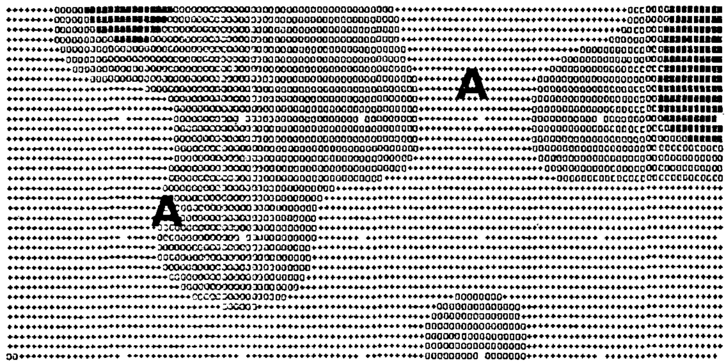
Spatial Variation

As upland forest hydrology is dominated by hillslope processes, some of the variation in moisture content may be explained by topographic features. Sandberg (1980) attributed the exclusion of duff moisture content from a model of duff consumption to its high variability and suggested stratification as a means of utilizing moisture content estimates in predictive equations. On the assumption that a site could be visually separated by areas of relative low moisture (exposed ridges), high moisture (draws and dense vegetation) and mid-slopes, stratification (often used to reduce variance) was explored. If the stratification is appropriate, the sample size necessary for an estimate within a predetermined allowable error should be less than a non-stratified estimate.

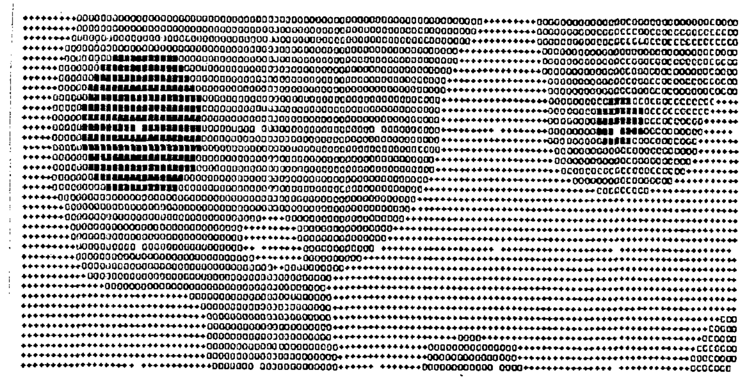
The computer generated maps for all sites are illustrated in Figures 8 to 12. With light shading representing dry areas and the dark shading, areas of highest moisture content, some regions of each PSME site do appear to remain in the same moisture regime throughout the season (labeled A on upper left map in each figure). Reference was earlier made to the high variability in depth at a single square meter point. There is a high likelihood that the inconsistencies seen on Figures 8 - 10 can be attributed to this as well. The thin duff generally found on the PSME sites, is more responsive to diurnal fluctuations and may be inadequately described by a sampling interval of 2 to 3 weeks. A single precipitation event may mask the hillslope hydrology controls over moisture distribution.

Figures 11 and 12, showing both layers of the ABLA sites, also have areas of consistent moisture relations but anomalies as well. Of special note is the similarity in moisture distribution of the layers and how they reflect the relationship established with the drying curves (Figure 5). For example, the upper layer of duff on Granite Ridge of 29 September had a much greater moisture content than the lower duff. Even without absolute values, Figure 11 indicates a vertical moisture distribution.

Downslope S 10 W

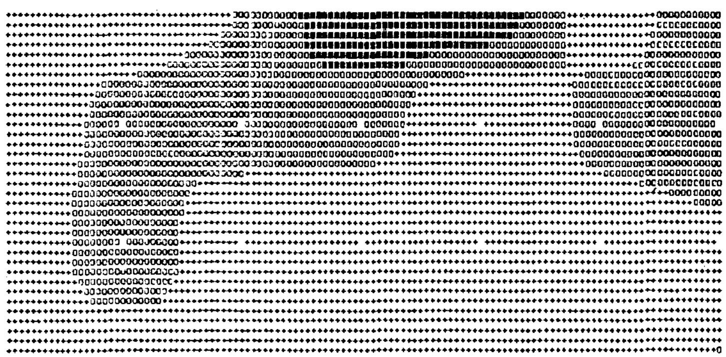


21 June 1982

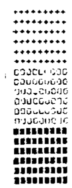


16 July 1982

6 July 1982



Legend (for Figures 8 - 12)

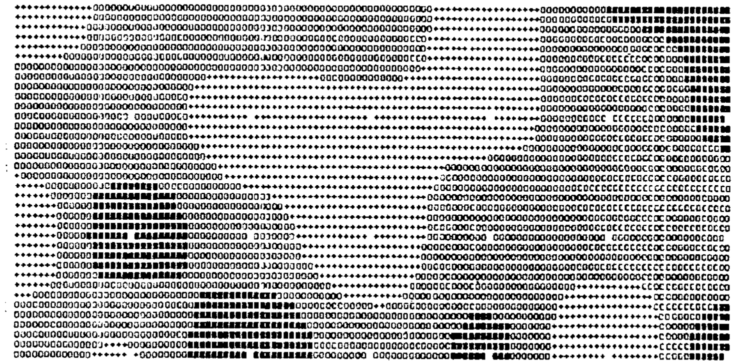


A area of seasonally consistent moisture relations

Blanks are sampling grid

Figure 8. Spatial distribution of duff moisture content on Cowboy Gulch study site. Maps represent an area 30 m x 60 m, identified by sampling date. Downslope edge with aspect is indicated on upper left map.

4 August 1981



15 September 1981

26 August 1981

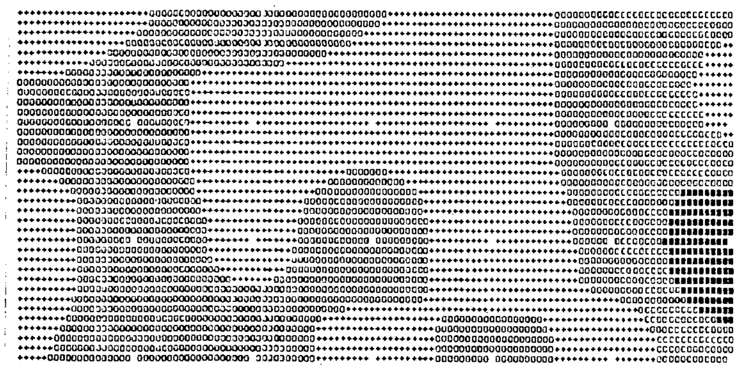


Figure 8. Cowboy Gulch continued.

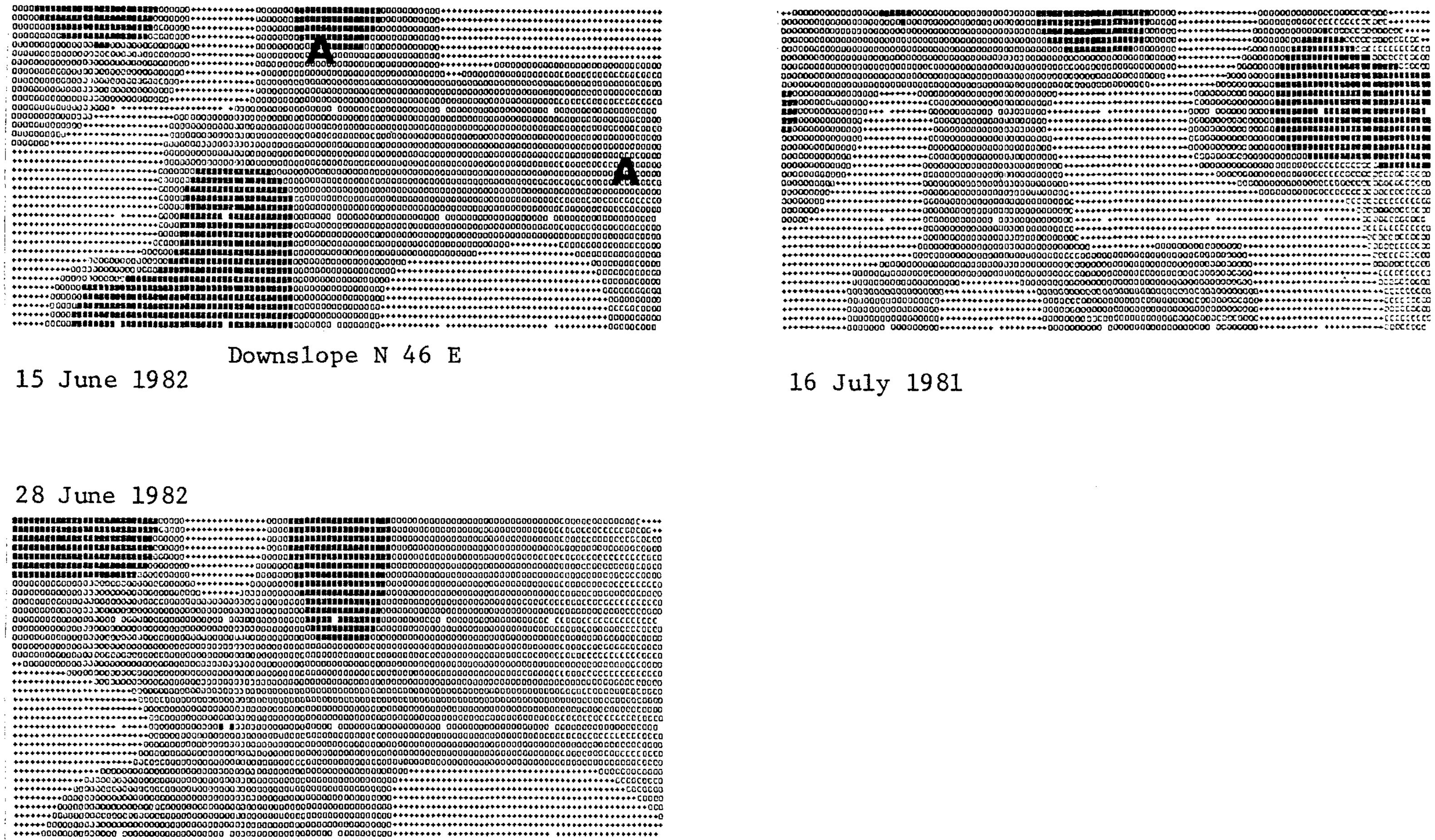
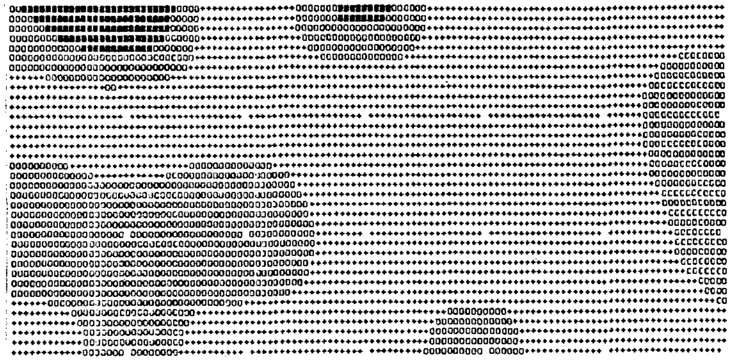
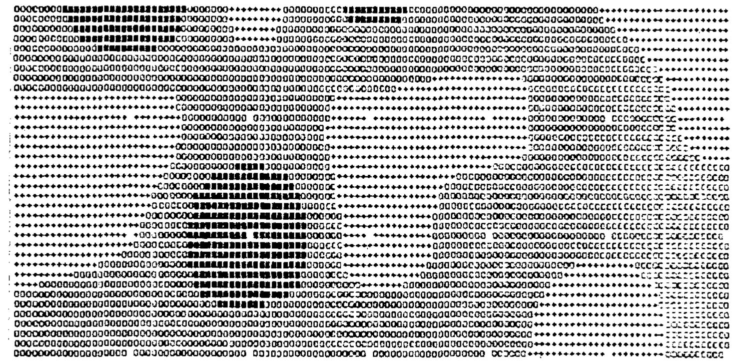


Figure 9. Spatial distribution of duff moisture content on Deer Creek site.

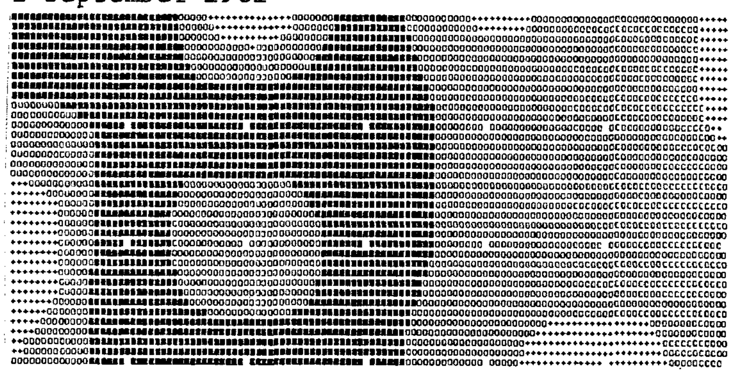


1 August 1981



14 September 1981

2 September 1981



5 October 1981

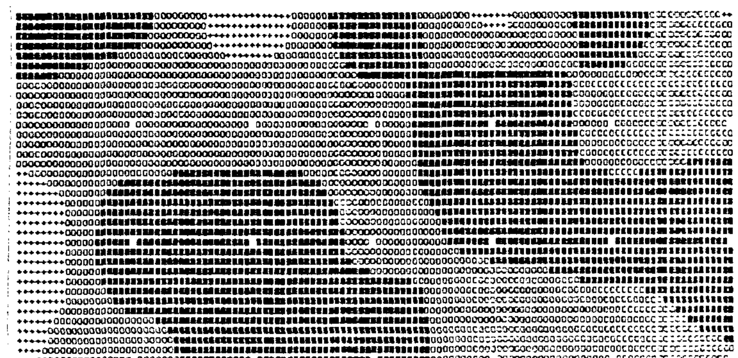
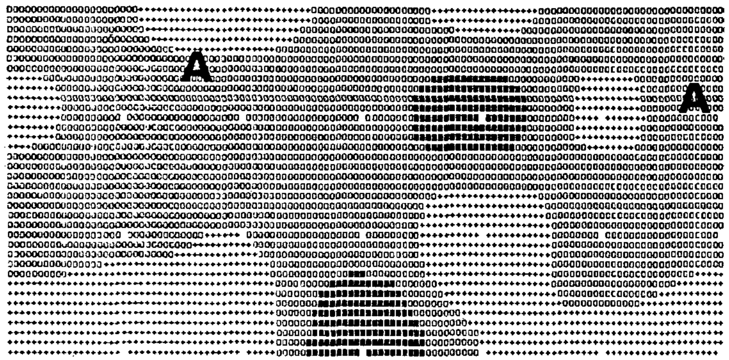
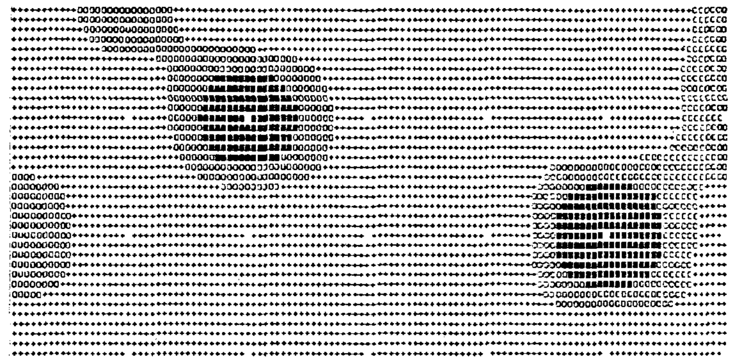


Figure 9. Deer Creek continued

Downslope S 5 W

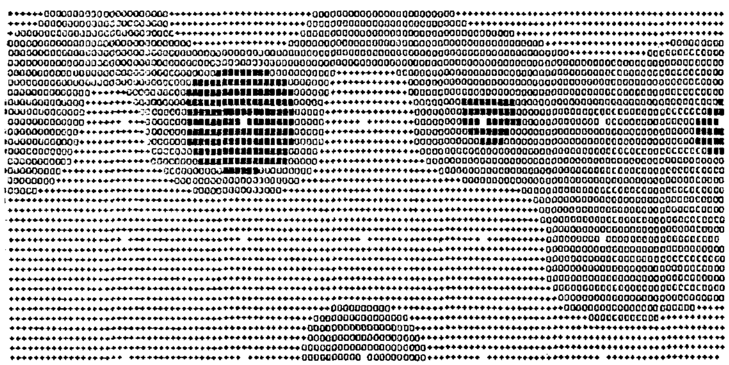


1 June 1982



21 July 1981

30 June 1982



3 August 1981

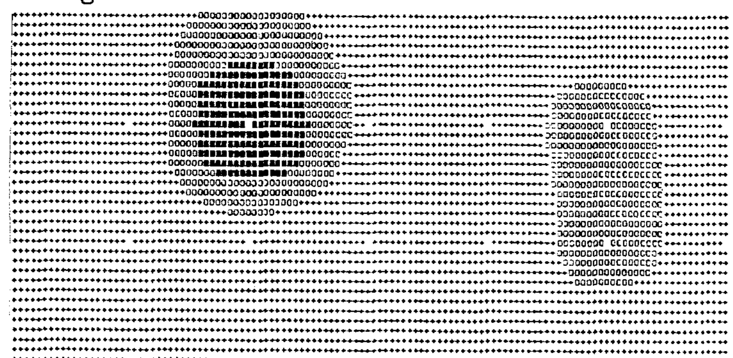
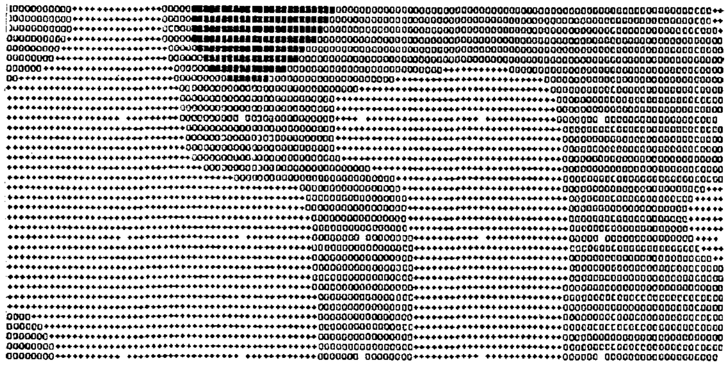
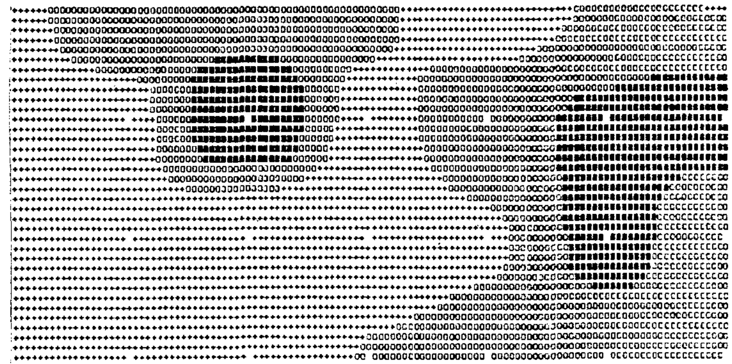


Figure 10. Spatial distribution of duff moisture content on Wagon Mountain site.



25 August 1981



6 October 1981

8 September 1981

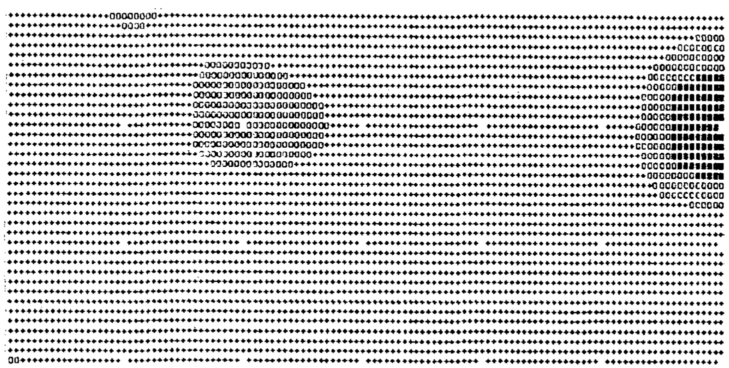
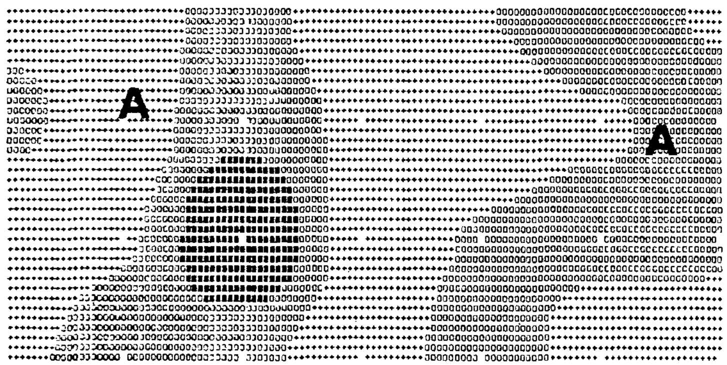
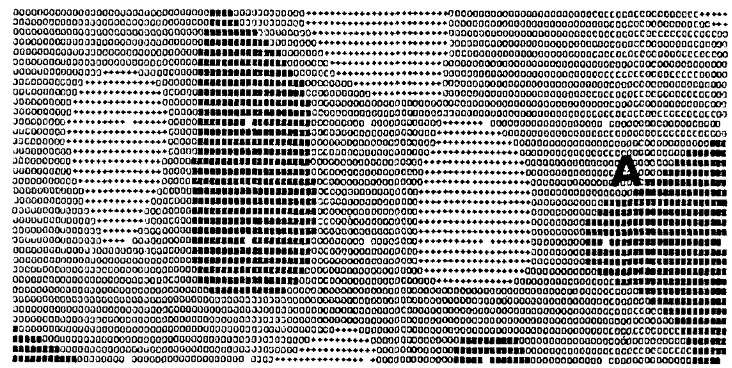


Figure 10. Wagon Mountain continued

Upper Duff

Lower Duff

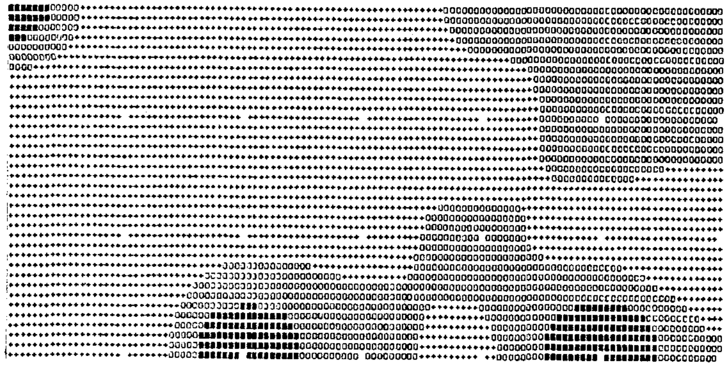




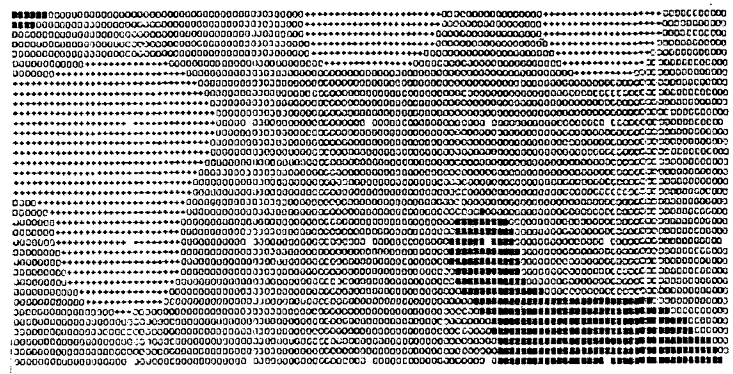
30 June 1982

Figure 11. Spatial distribution of duff moisture content in upper (left) and lower (right) duff layers at Granite Ridge study site. The aspect is N 10 E. The lower edge is downslope.

Upper Duff

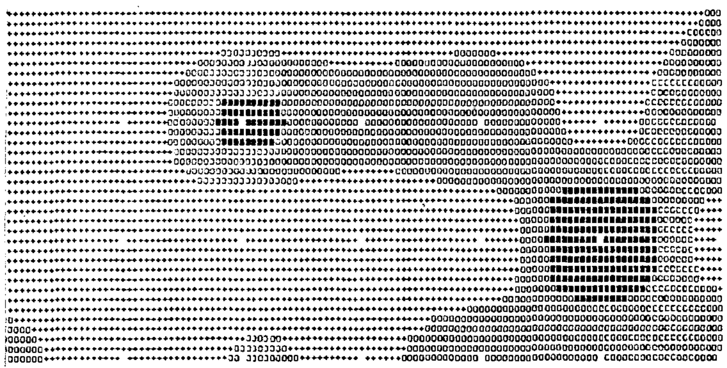


Lower Duff



13 July 1982

17 August 1981



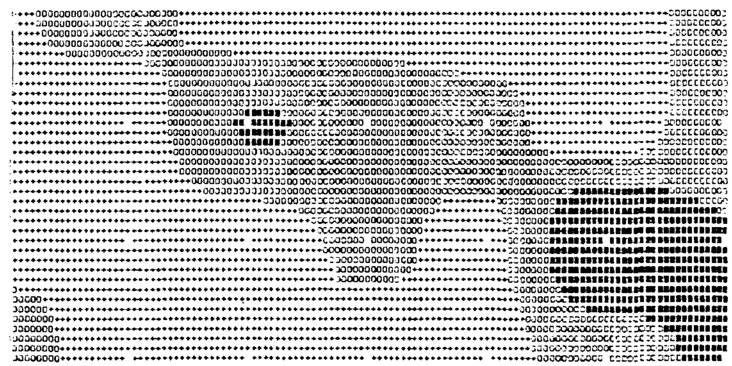
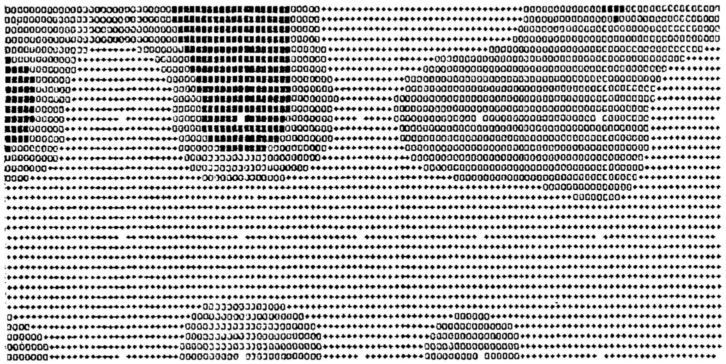
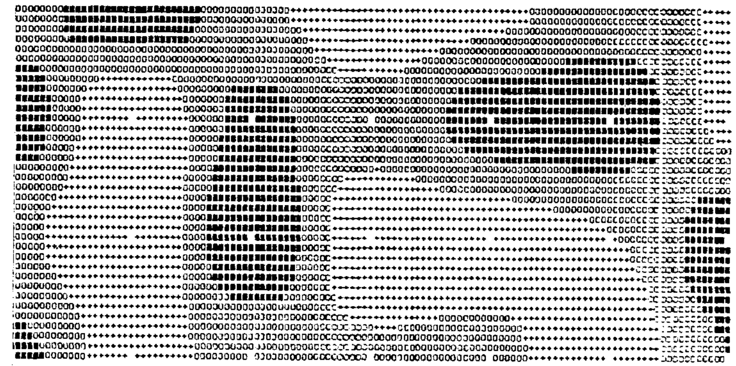


Figure 11. Granite Ridge continued

Upper Duff



Lower Duff



8 September 1981

21 September 1981

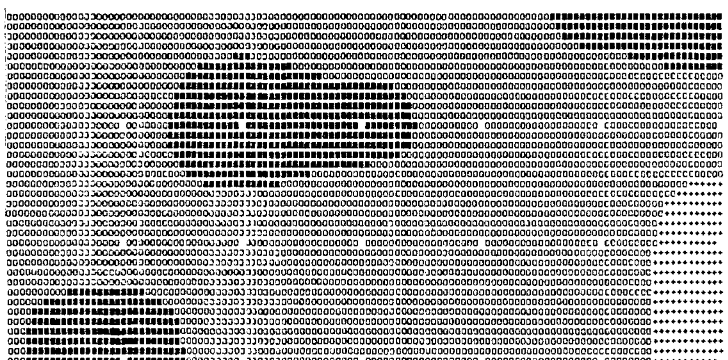
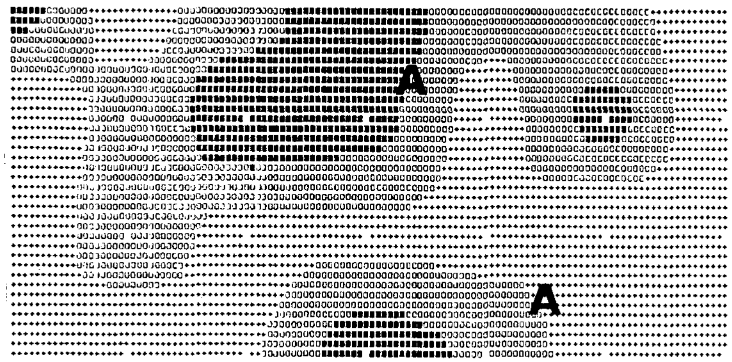
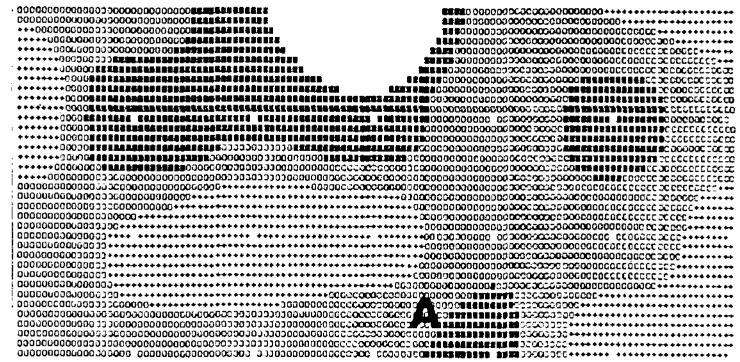


Figure 11. Granite Ridge continued

Upper Duff

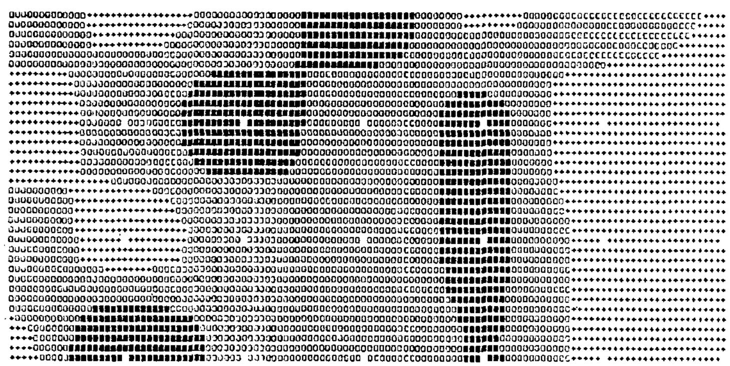


Lower Duff



22 June 1982

13 July 1982



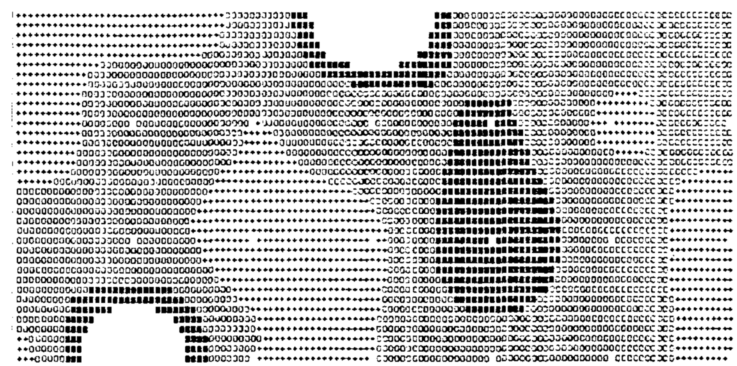
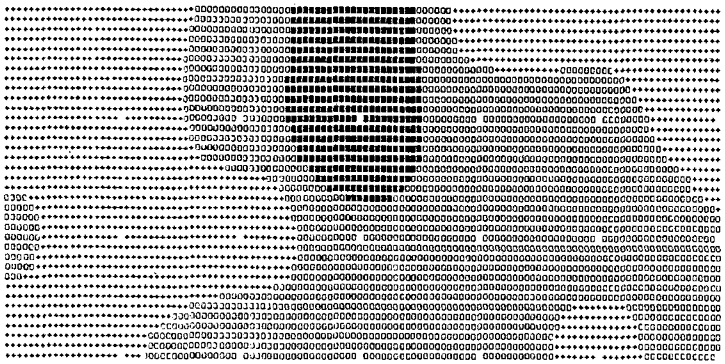
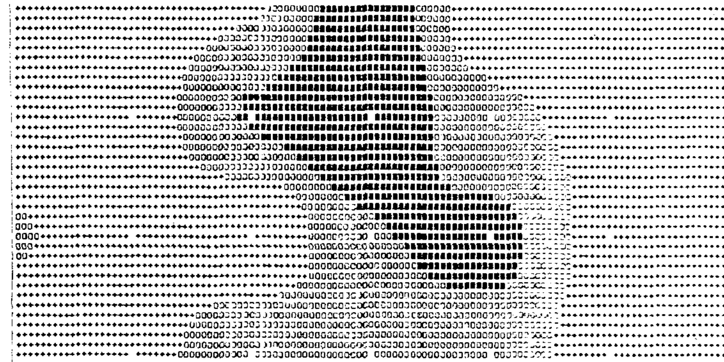


Figure 12. Spatial distribution of duff moisture content in upper (left) and lower (right) duff layers at Lee Creek study site. Aspect is N 10 W, lower edge is downslope.

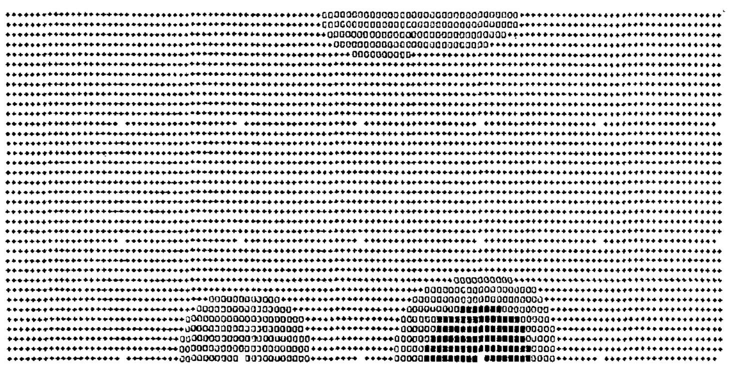
20 July 1981 Total Layer



3 August 1981 Total Layer



Upper Duff 24 August 1981 Lower Duff



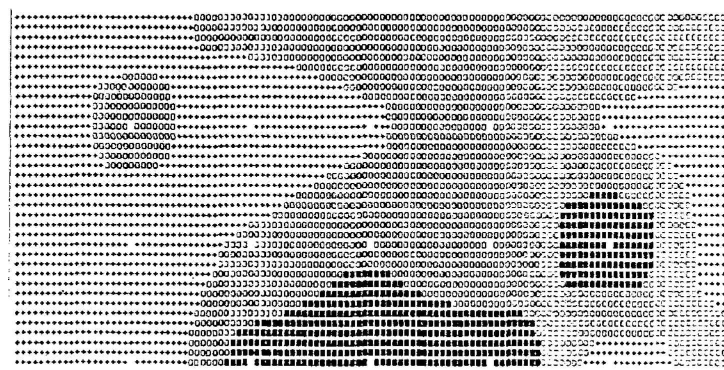
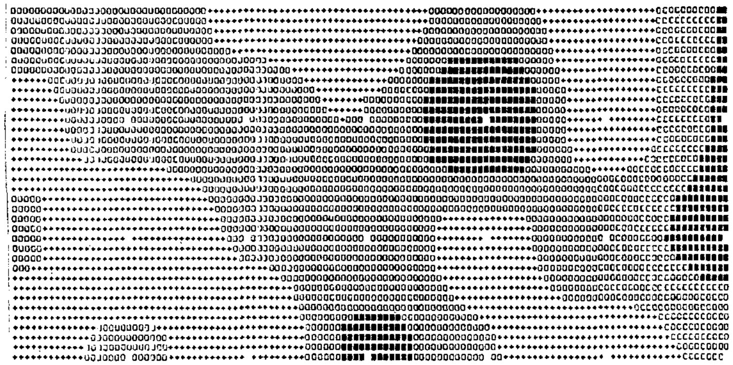
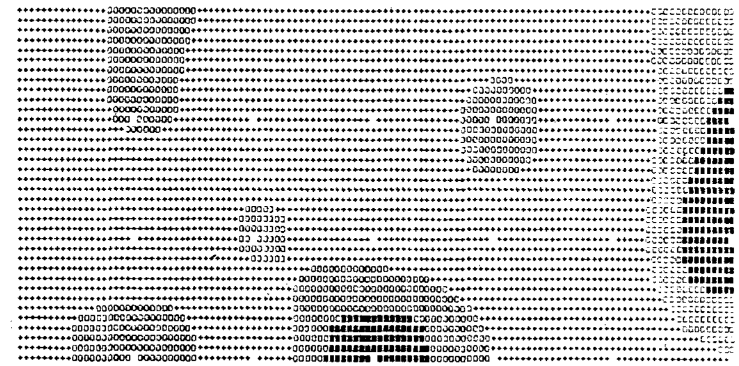


Figure 12. Lee Creek continued. Upper figures show total duff moisture distribution.

Upper Duff

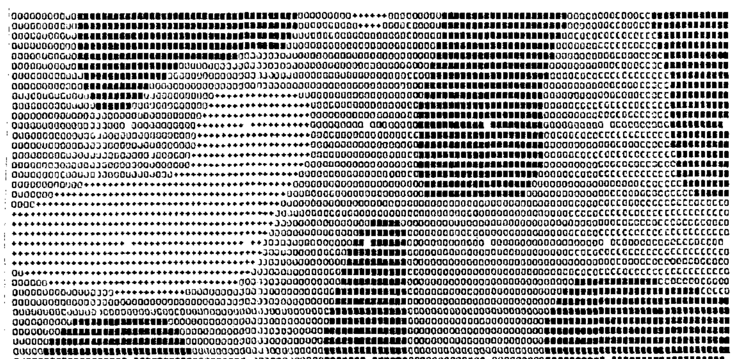


Lower Duff



4 September 1981

29 September 1981



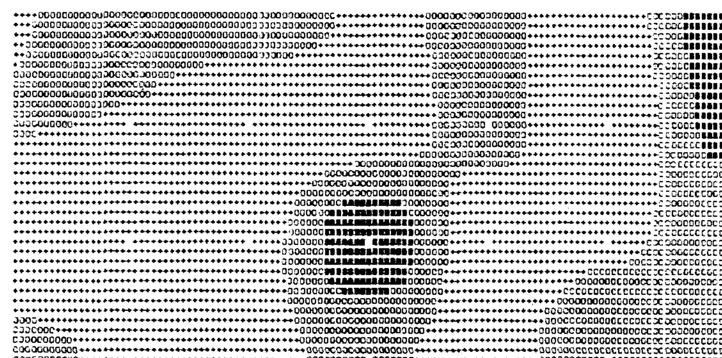


Figure 12. Lee Creek continued

Sample size

Calculations for sample size estimates depend on a reasonable error term. Acknowledging the tremendous variation in duff moisture on a site, 20% error is adequate (K. Ryan, NFFL, Pers. Comm.). Table 4, allowable error estimates from four of the sites, shows results that support the use of a 20% error.

Table 5 presents the results of calculating n by Equation 7 (non-stratified) and Equation 9 (stratified). The stratified sample has a significant reduction in sample size. A minimum stratified sample size of three allocates one sample per strata, but does not provide an estimate of variance, required for Neyman allocation. The sensitivity of sample size to estimated areal proportions can be determined by experimentally increasing or decreasing the proportions. When a 20% change in the area of the mesic regime on Cowboy Gulch and Deer Creek was tested, the sample size was within one unit of the original calculations. A larger sample size than that calculated at an allowable error of .20 will not detract from the estimate but will increase its accuracy. These results suggest that site stratification may be a desirable strategy for sample size reduction while retaining a reliable estimate of the mean

Table 4. Allowable Error associated with non-stratified sampling by site assuming two confidence levels.

$$a^2 = t^2 CV^2 (1/n - 1/N)$$

Site	Confidence Level 90%	95%	Site	Confidence Level 90%	95%
PSME sites					
C621	21.5	25.9	D615	17.6	21.2
C706	11.5	13.8	D628	15.6	18.8
C718	14.7	17.7	D716	15.0	18.1
C804	12.1	14.6	D801	16.0	19.0
C826	10.7	13.0	D902	12.4	15.0
C915	8.9	10.7	D914	12.1	14.6
			D005	10.5	12.7
Mean	13.2	15.9		14.1	17.0
ABLA sites (upper duff)					
G630	7.5	9.0	L622	20.2	24.3
G713	24.6	29.6	L713	16.1	19.3
G817	17.3	20.8	L824	21.1	25.4
G908	19.8	23.9	L904	13.3	16.0
G929	6.5	7.9	L929	10.5	12.7
Mean	15.1	18.2		16.2	19.5
(lower duff)					
G630	9.0	10.9	L622	14.5	17.5
G713	10.0	12.0	L713	11.7	14.2
G817	18.7	22.5	L824	12.0	14.5
G908	14.0	16.9	L904	16.7	20.1
G929	8.9	10.8	L929	14.1	17.0
Mean	12.1	14.6		13.8	16.7
(total duff - Lee Creek only)					
			L720	16.4	19.8
			L803	20.0	24.1

Table 5 - Sample Size by site and date at two confidence levels using systematic, non-stratified and stratified sampling techniques, assuming an allowable error (a) = .20

	Without Stratification		With Stratification	
	Confidence Level		Confidence Level	
	90%	95%	90%	95%
PSME sites				
C621	33	47	6	8
C706	10	14	3	3
C718	16	22	5	7
C804	11	15	3	3
C826	9	12	3	4
C915	6	9	3	3
D615	22	32	4	6
D628	18	25	4	5
D716	16	23	4	5
D801	18	26	4	6
D902	11	16	3	4
D914	11	16	3	5
D005	8	12	3	3
W601	15	21	4	5
W630	7	11	3	3
W721	33	44	5	7
W803	16	23	4	5
W825	17	24	5	6
W908	27	39	6	8
W006	18	26	4	5
ABLA sites				
G630	4	6	3	3
G713	42	61	8	12
G817	21	31	6	8
G908	28	40	5	7
G929	4	5	3	3
G630(L)	6	9	3	4
G713(L)	7	11	3	4
G817(L)	25	35	6	8
G908(L)	14	21	3	4
G929(L)	6	9	3	4

Table 5 - Sample Size (cont.)

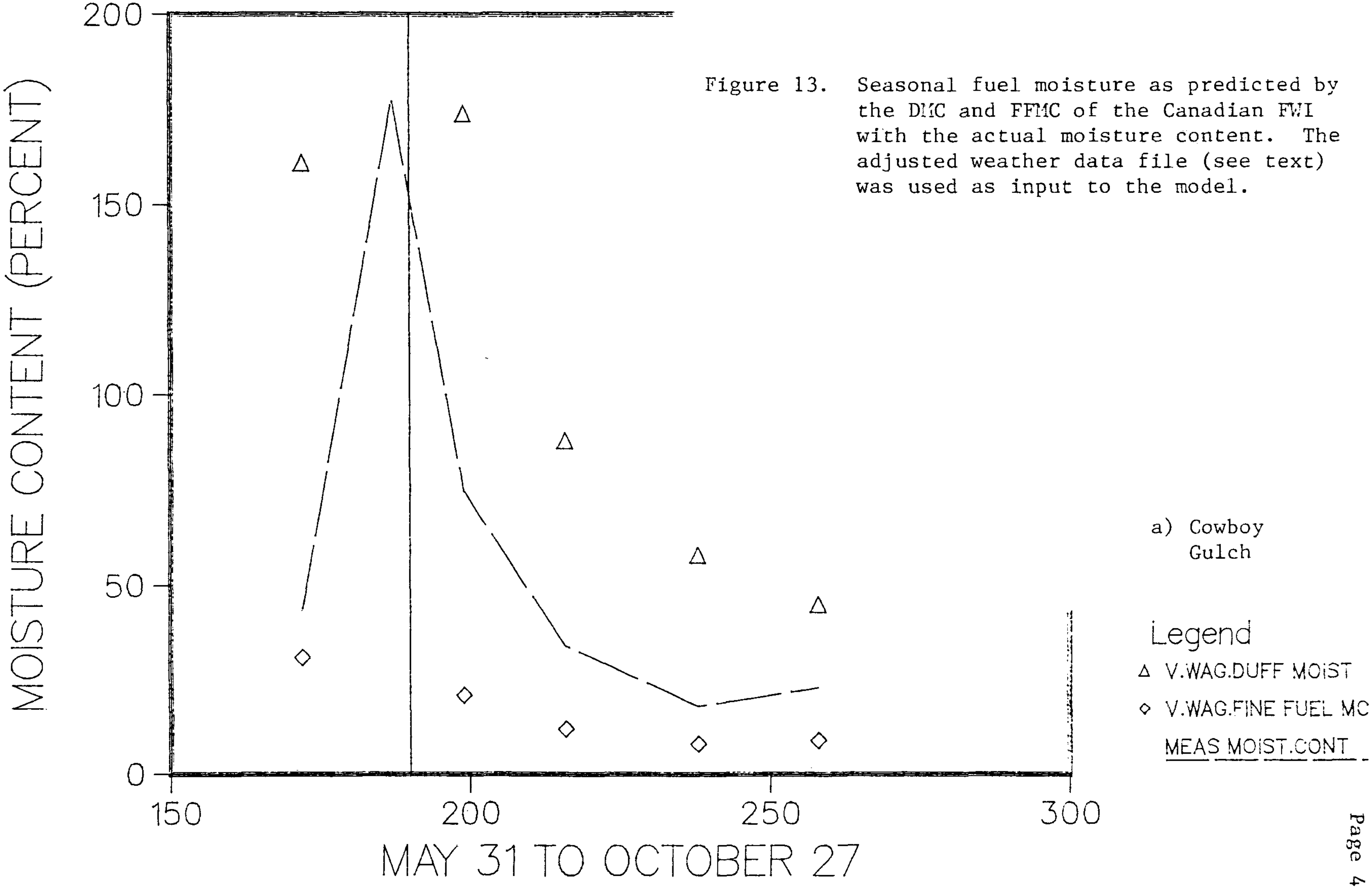
	Without Stratification Confidence Level		With Stratification Confidence Level	
	90%	95%	90%	95%
L622	29	42	5	7
L713	19	27	4	6
L720(T)	19	28	4	5
L803(T)	28	41	5	7
L824	32	45	6	8
L904	13	19	4	5
L929	8	12	3	4
L622(L)	15	22	3	4
L713(L)	10	15	4	5
L824(L)	11	15	4	5
L904(L)	20	29	6	8
L929(L)	15	21	5	7

Fuel Moisture Models

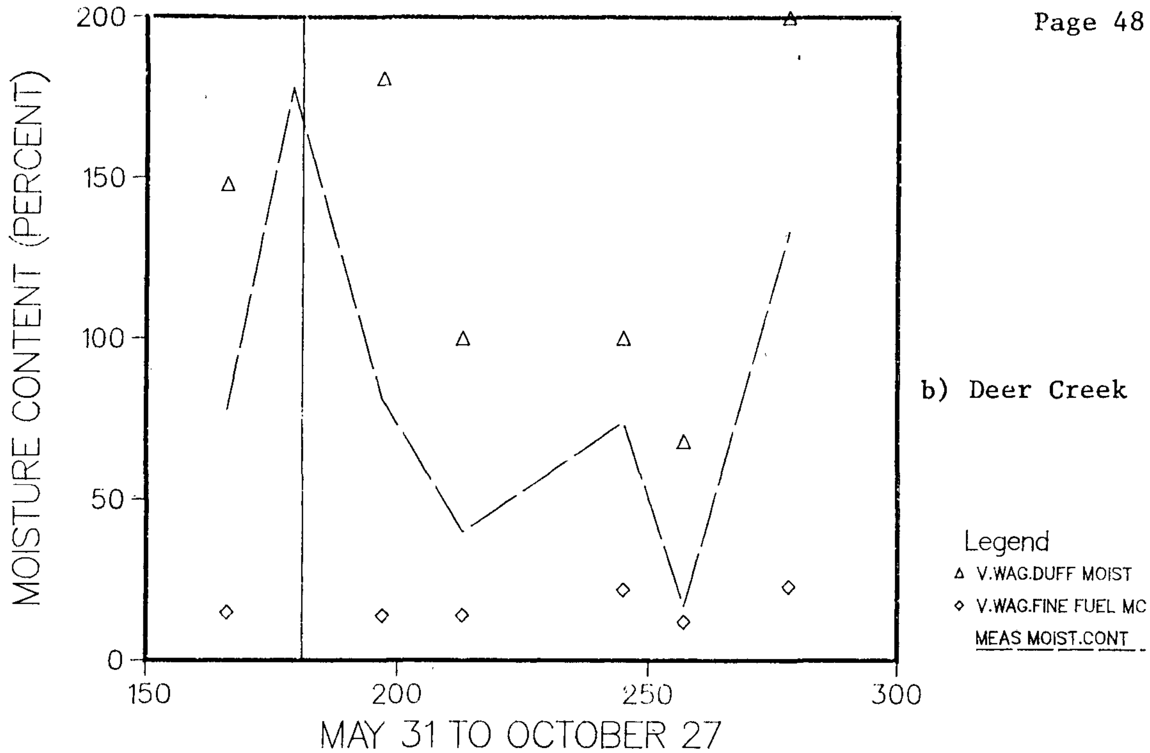
The predicted values of the FFMC and DMC of the Fire Weather Index are plotted with measured data in Figures 13a - e. Neither set of coded values predicts the actual values but both do track the expected drying regime. The FFMC, developed for fine litter with an average weight of 0.24 kg/m^2 (0.05 lb/ft^2) was appropriate for the drier periods on the PSME sites and upper duff moisture of the ABLA sites. A site by site adjustment would improve the predictive capability of the FFMC.

The DMC was derived from measurements of duff with a weight of 4.88 kg/m^2 (1 lb/ft^2). On the PSME sites, the moisture content was overestimated by this code. It is a better estimator of the lower duff moisture content from the ABLA sites, but there is still a large offset

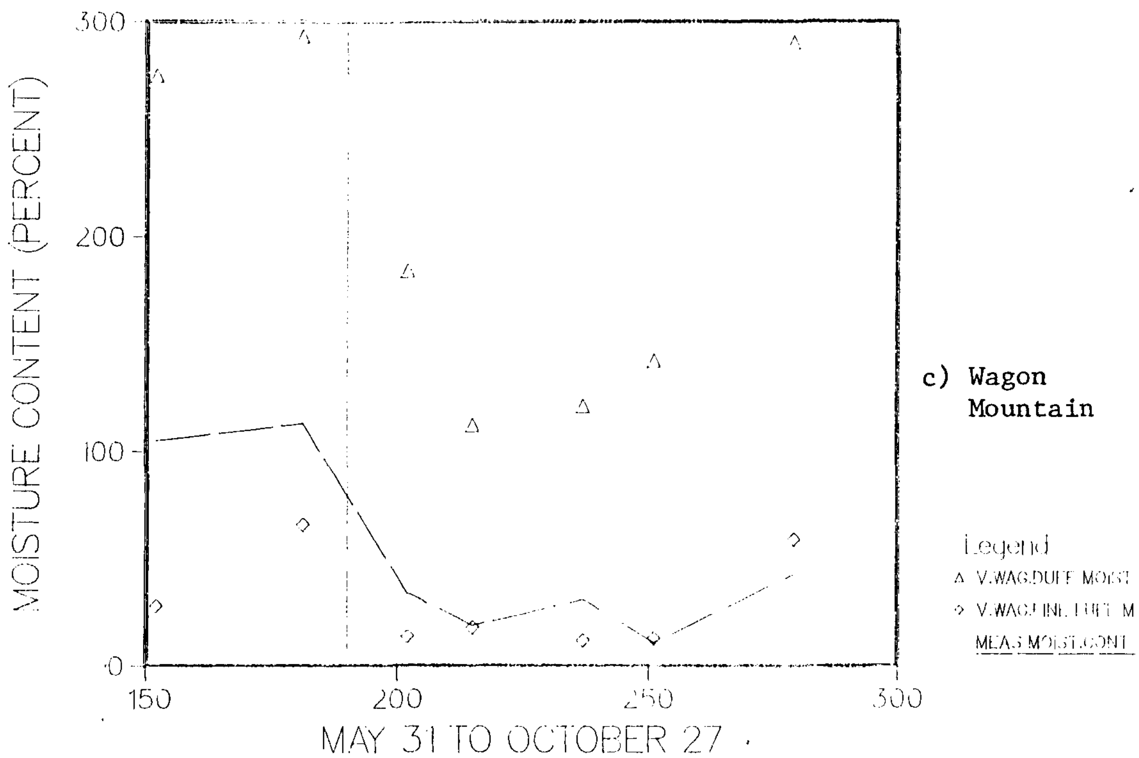
Figure 13. Seasonal fuel moisture as predicted by the DMC and FFMC of the Canadian FWI with the actual moisture content. The adjusted weather data file (see text) was used as input to the model.



a) Cowboy Gulch

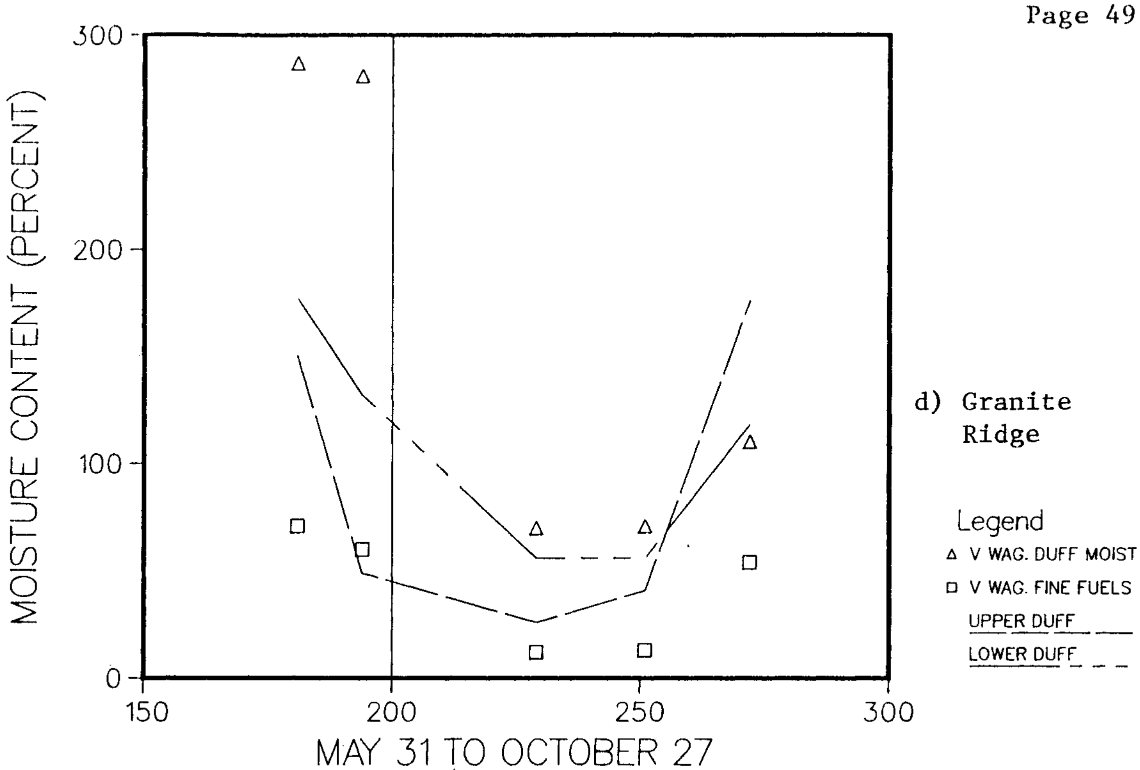


b) Deer Creek

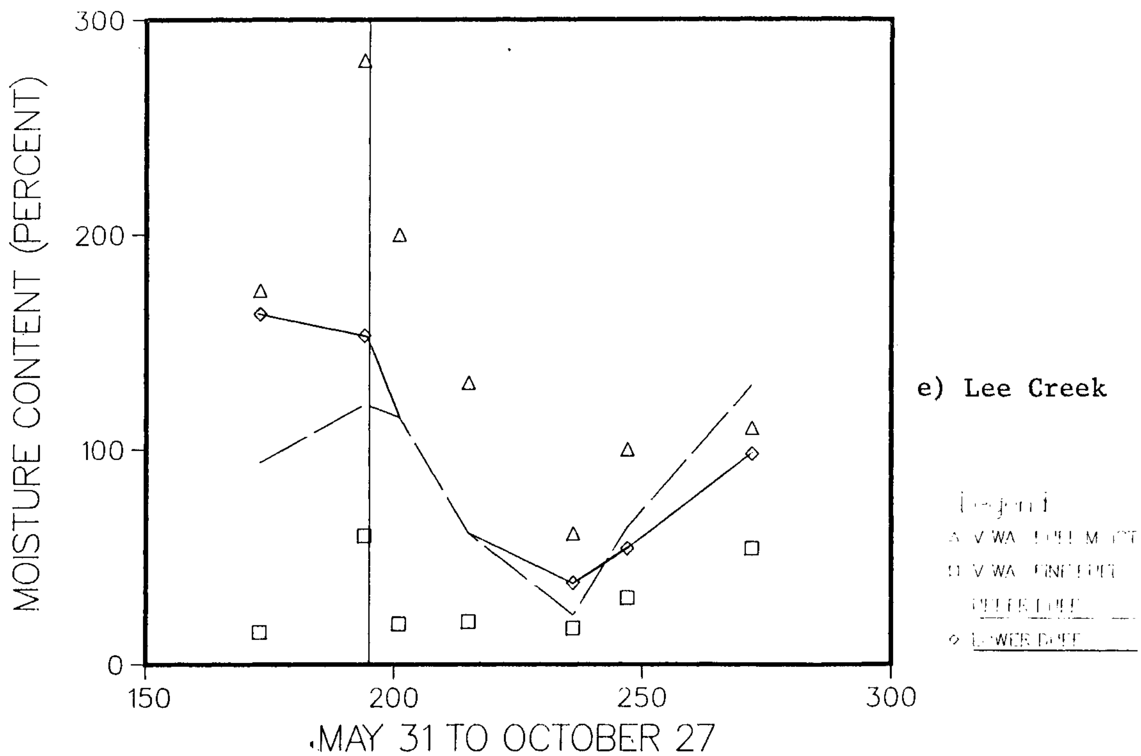


c) Wagon Mountain

Figure 13. Seasonal fuel moisture models (cont'd).



d) Granite Ridge



e) Lee Creek

Figure 13. Seasonal fuel moisture models (cont'd).

(Figs 13d,e). This discrepancy suggests that the duff encountered in this study would best be described by some intermediate code or by an averaged value of the FFMC and DMC.

As discussed in reference to the accuracy of timelag estimates, the split season and late start of sampling in 1981, when the duff was well into a drying phase, limited the utility of the models. The individual fuel codes or models of the FWI model (Van Wagner and Pickett 1975) and DANRAT, because of their derivation, require one to several weeks to stabilize, with the models representing larger fuels taking longer. Because of this data requirement, the NFDRS predictors from the ABLA sites in 1982 were unreliable.

Using an analysis similar to Sandberg (1980), the actual duff moisture data (ADM) from the PSME sites were regressed against the NFDRS timelag fuel estimates calculated by DANRAT:

1-hour	ADM = 31.3 + 1.01(1-hour)	r^2 = .04
10-hour	ADM = 15.1 + 2.62(10-hour)	.20
100-hour	ADM = -34.1 + 5.79(100-hour)	.40
Th-hour	ADM = -30.0 + 4.54(Th-hour)	.30

Whereas Sandberg (1980) found a strong predictive capability from the 1000-hr (NFDRS-Th), these linear regressions indicate that for this duff type, the 100-hr is the best predictor. Figure 14, however, is a plot of ADM with the 100-hr and 1000-hr estimates on a per site basis. The regression equations for the 100-hr are given below:

Cowboy	ADM = -55.2 + 8.66(100-hr)	r^2 = .90
Deer Cr	ADM = -86.1 + 10.3(100-hr)	.78
Wagon Mtn	ADM = -10.6 + 2.62(100-hr)	.38

The scatter around the regression on each site is much less than for the cover type regression and indicates that a general predictive equation, although useful, should be used with reservation.

In summary, the fuel moisture models can be used for these sites but they must be verified. The FWI and NFDRS moisture estimates were calculated using some assumptions because of the inadequacies in the data. Duff from PSME sites similar to those studied should be well described at the driest periods by the Canadian FFMC and by the 100-hr estimate. The moisture content of deeper duff such as found on ABLA sites was overpredicted by the DMC of the FWI.

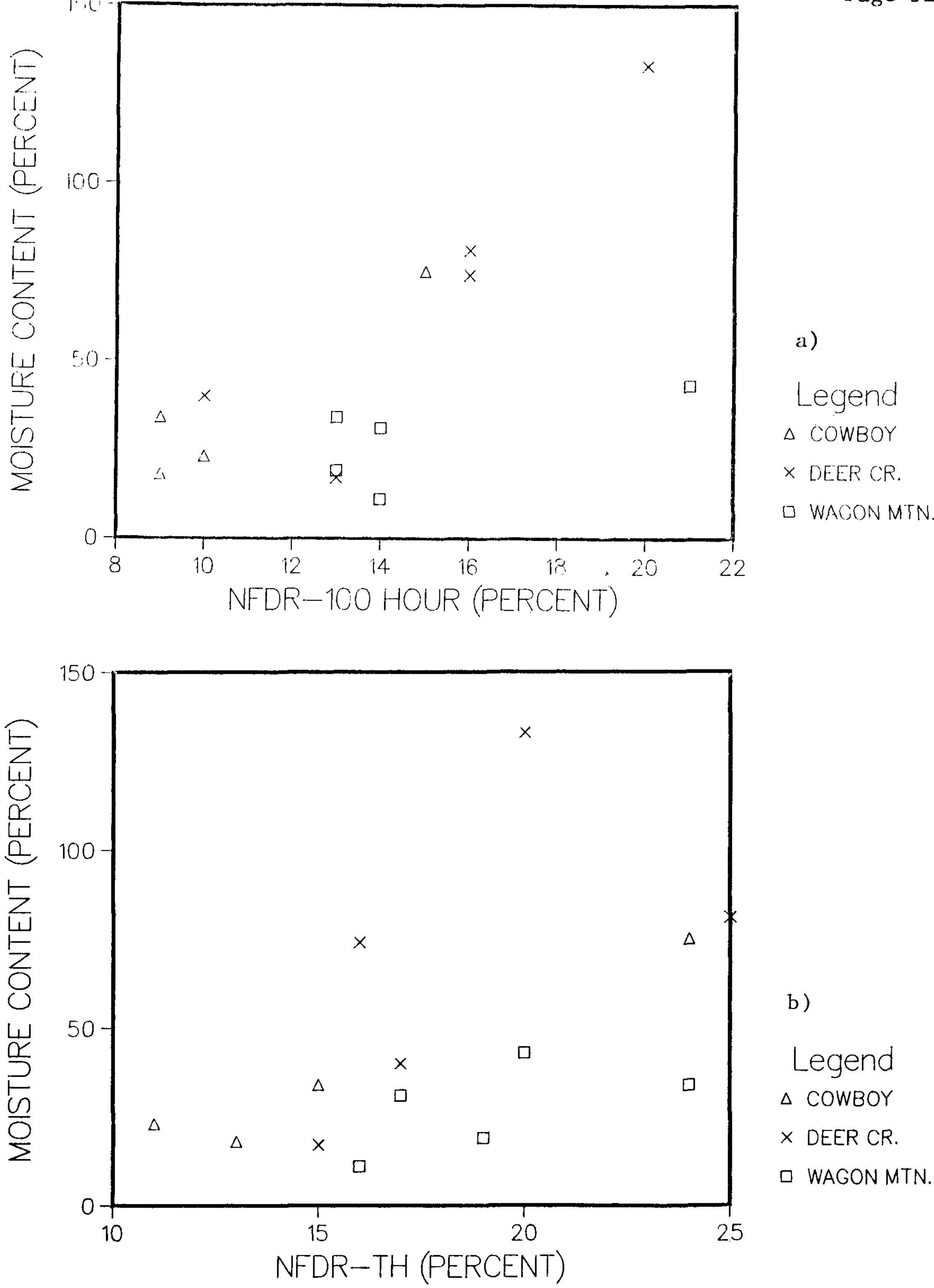


Figure 14. Regression of actual duff moisture content on a) NFDRS 100-hr timelag moisture estimate and b) NFDRS 1000-hr timelag estimate.

CHAPTER V

MANAGEMENT IMPLICATIONS

In this study, the spatial pattern of moisture content was determined from the collected data. The correspondence of the three moisture regimes to topographic features suggests that strata may be delineated by topography prior to sampling. Draws and dense vegetation should be considered "wet" and ridges or exposed areas may be described as "dry."

The equation for sample size determination (Equation 8) requires estimates of strata variances. The coefficient of variation (CV) can also be used as in Stauffer (1982). A relationship between the mean and CV as Figure 7 illustrates, gives some indication of the expected variation at different moisture contents. The "envelope curve" described by Owe et al. (1982) would provide a safe maximum estimate of CV as most of the values lie below the curve and high CV's give high sampling numbers.

Table 5 showed the significant reduction in sample size achieved through stratification. As a general guideline, the maximum stratified sample size required was 8 samples on PSME/PHMA sites and 12 samples on the ABLA/MEFE sites.

Allocation of samples among strata can be calculated by several methods, depending on the amount of known information. Proportional allocation requires samples to be distributed between strata as each strata is proportioned to the entire area. Neyman allocation uses an estimate of stratum variances to allocate the samples, and thus requires more information and more calculation. As an allowable error of .20 was assumed, these extra steps may not be justifiable.

To use this technique, a site would be stratified by topographic features, resulting in three strata. An estimate of variation provides the information to calculate sample size. Two random samples of duff moisture should be taken from each stratum for an estimate of variance. The remainder of the samples may be allocated in proportion to the area each stratum occupies, with the total sample size of 12 on the wetter sites and 8 on drier sites.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Duff structure was found to exhibit high variation on all the sites. Physical site characteristics such as slope and aspect and cover type distribution as controlled by site may account for much of the variation. The sites of a given cover type exhibited less variation than did the two cover types.

The variation in duff moisture content can be significantly reduced by a stratification scheme based on relative moisture regimes. This stratification appears consistent through a season. Stratification permits sample size reduction at any level of accuracy. The stratification is judgemental but the potential error in designating proportions does not significantly affect the calculated sample size.

In conclusion, this research has shown that for sites of similar characteristics to those studied and scheduled for prescribed fire, stratification into three moisture regimes, most easily corresponding to topographic features, can greatly decrease the costs and improve the efficiency of the estimator. Sandberg (1980) did not consider stratification feasible for field application. However, field personnel can recognize the extremes of moisture - the driest and wettest regions. As efficient sampling produces maximum information about a population for minimum costs of time and resources, these three strata should provide sufficient samples for a duff moisture estimate.

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